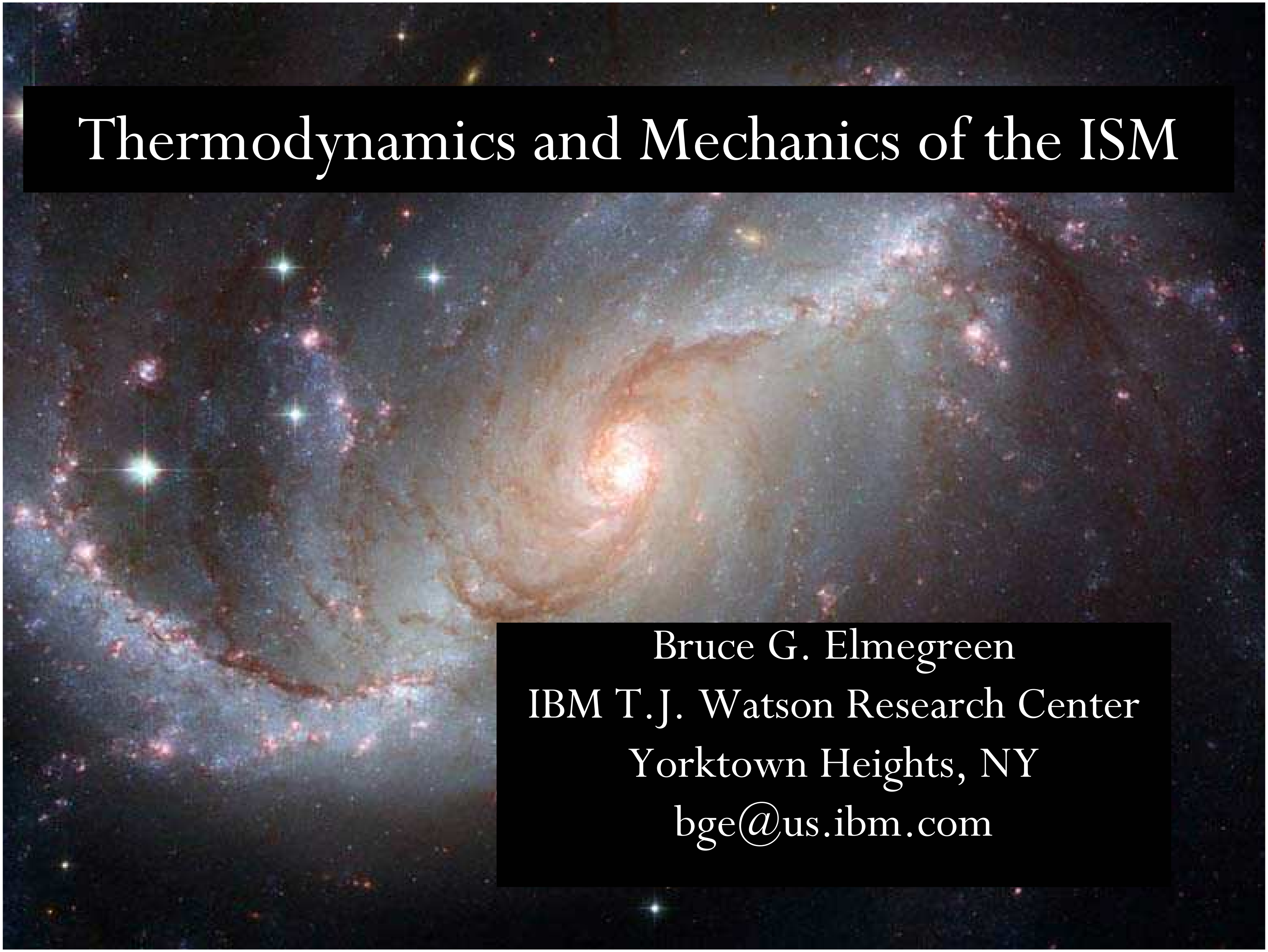
Thermodynamics and Mechanics of the ISM



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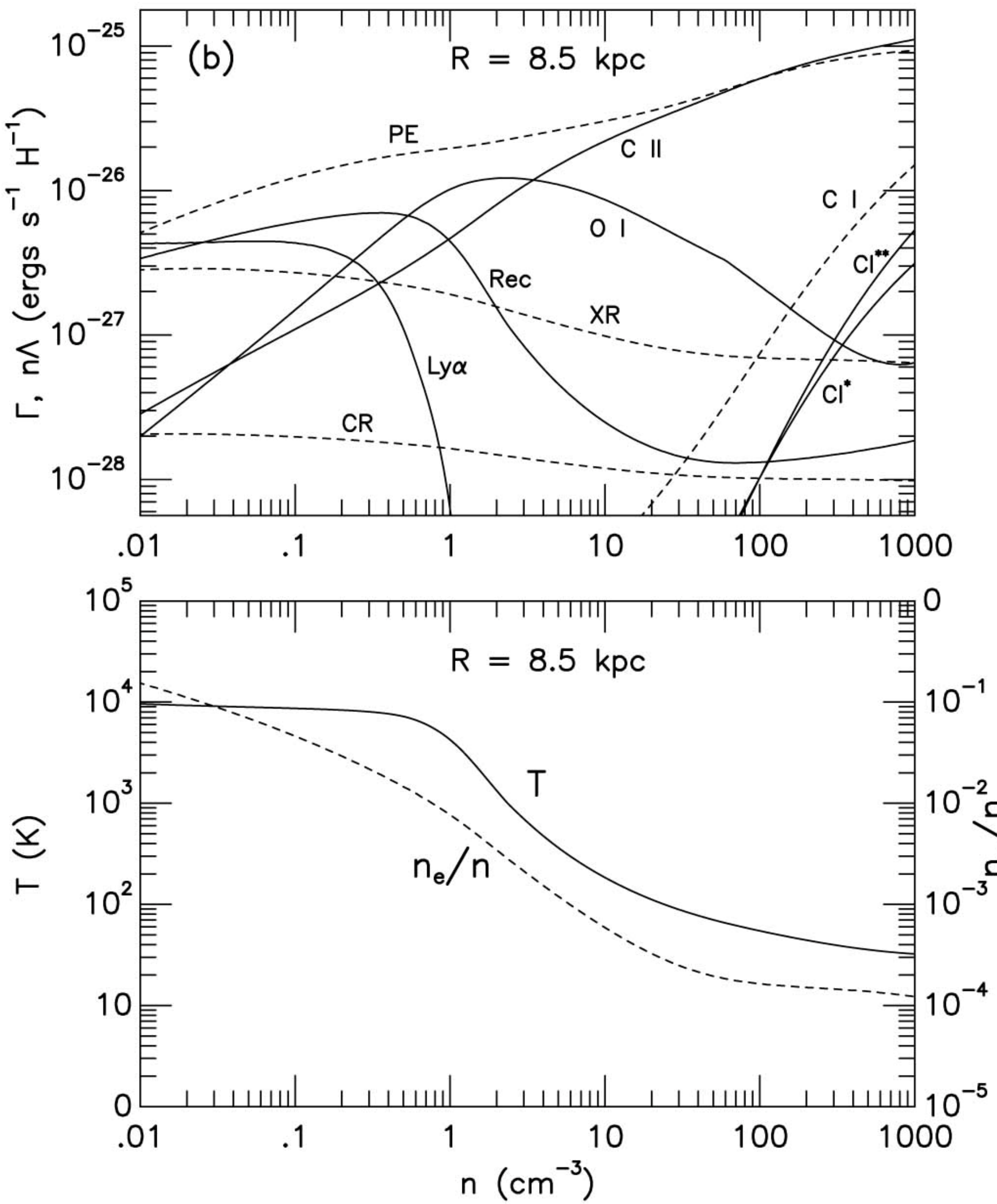
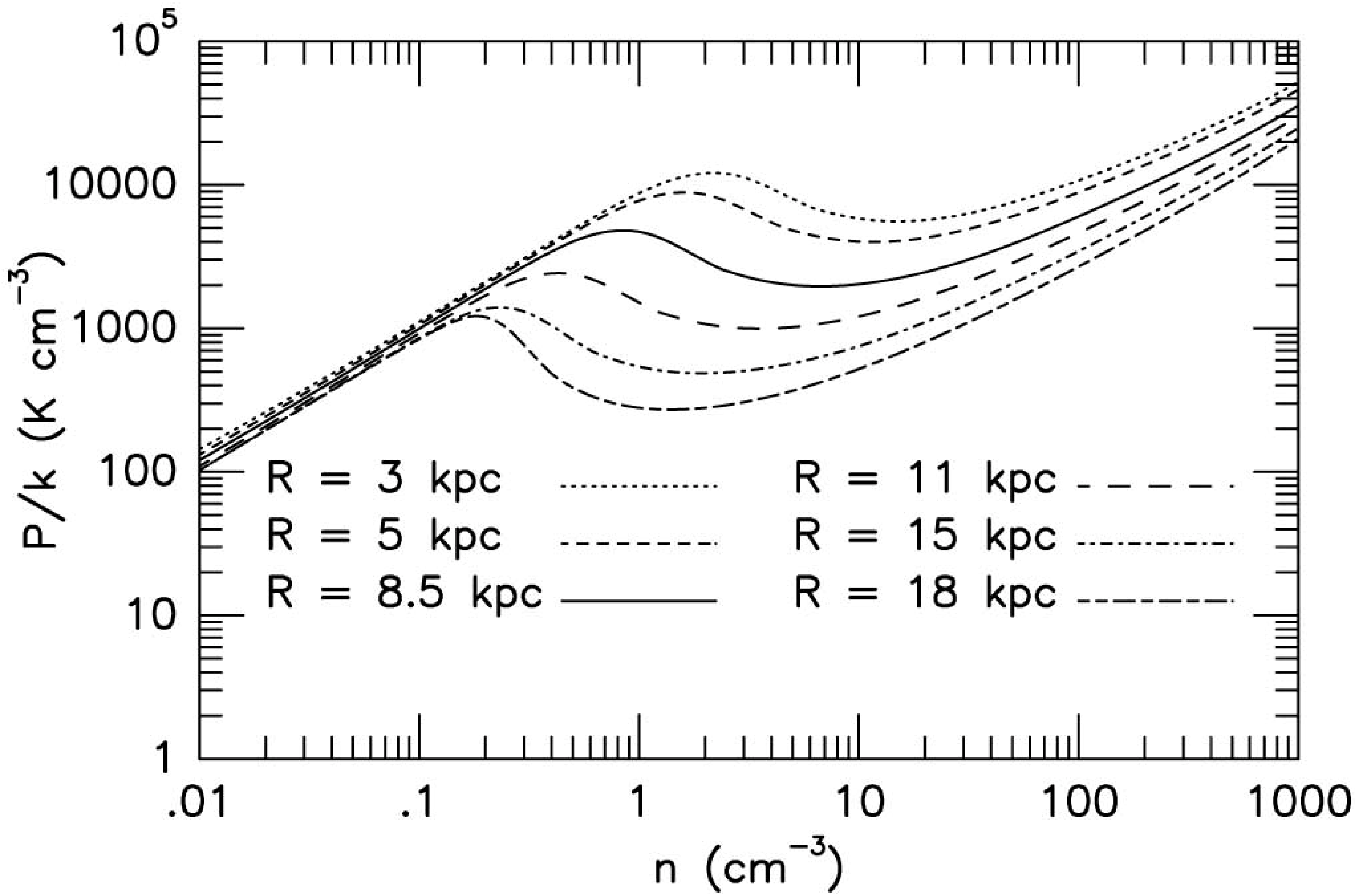
Concepts of Equilibrium

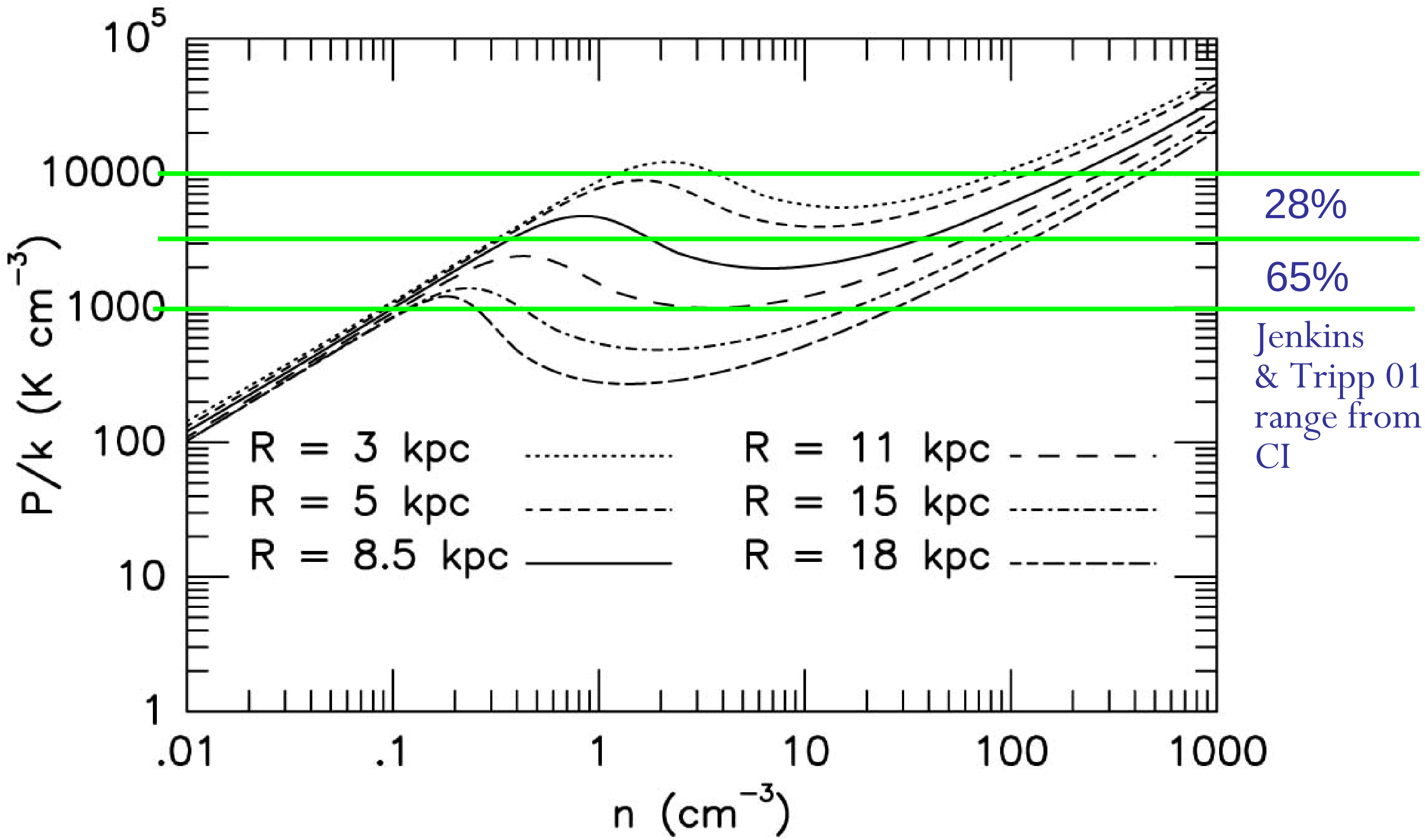
- Thermal/Mechanical equilibrium
  - thermal equilibrium determines cool/warm phase properties

Wolfire + 03 heating and cooling versus density for the atomic phases



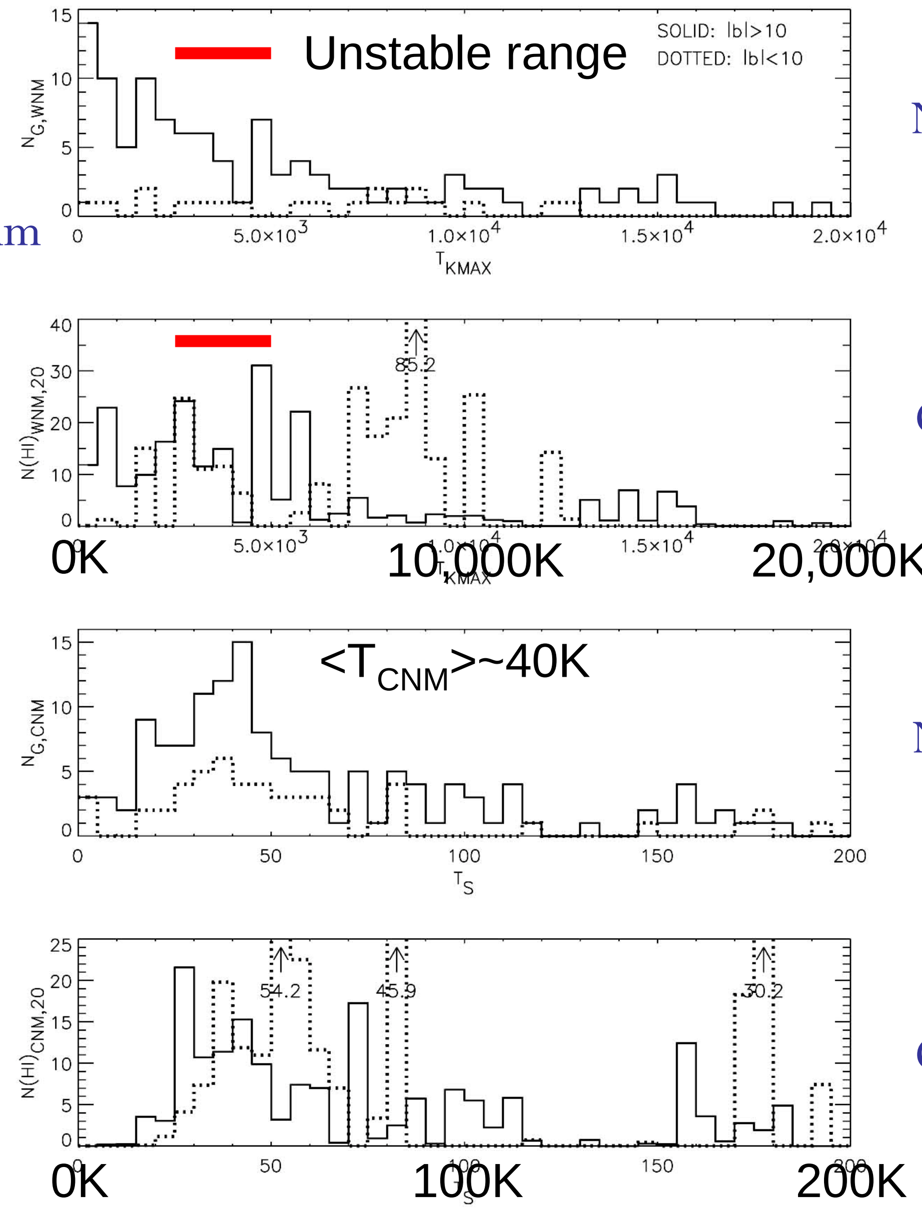


Wolfire +03: Phase diagrams for the Milky Way, for different radii.



Wolfire +03: Phase diagrams for the Milky Way, for different radii.

Warm Neutral Medium



Number of components

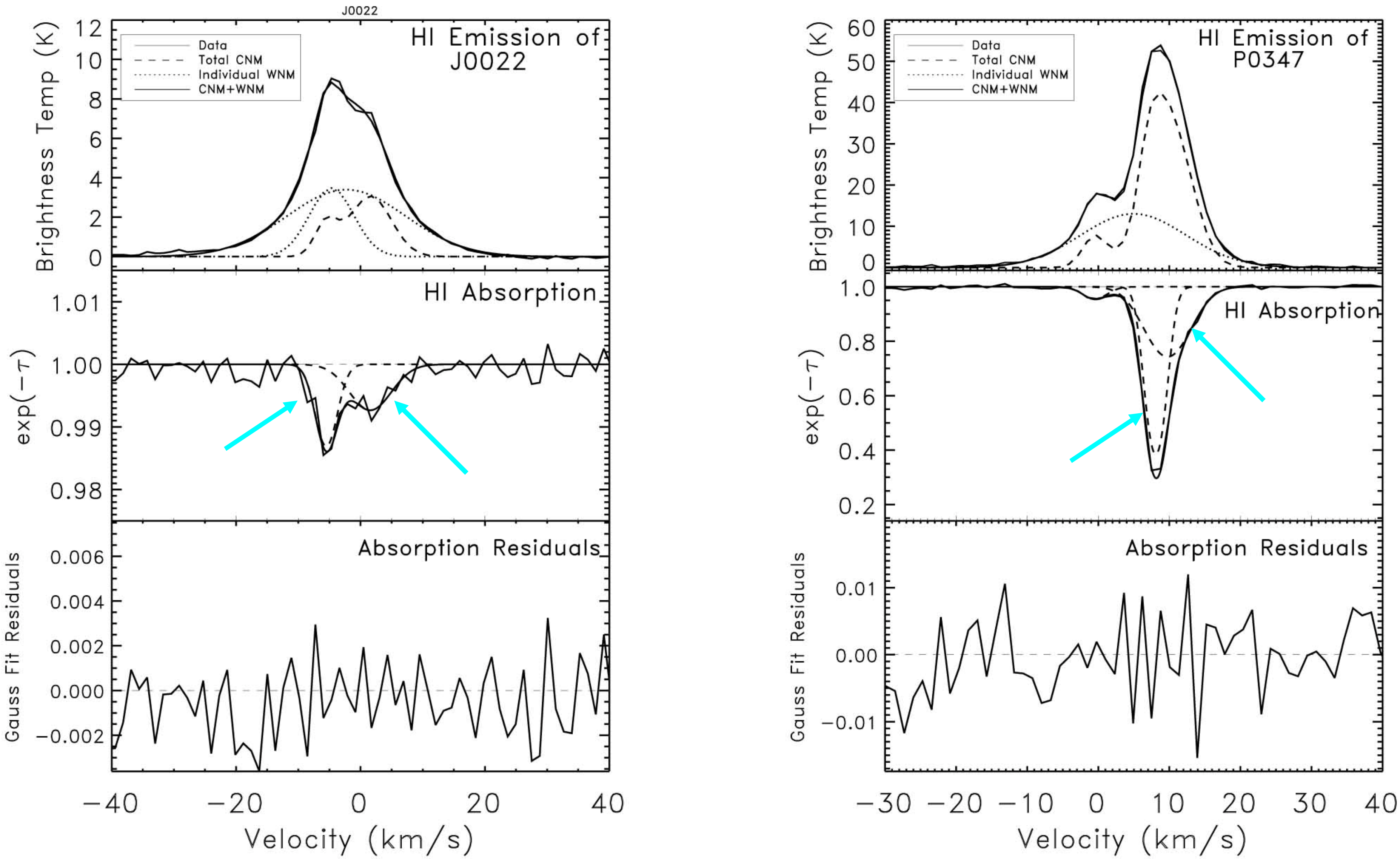
Column densities

Cold Neutral Medium

Number of components

Column densities

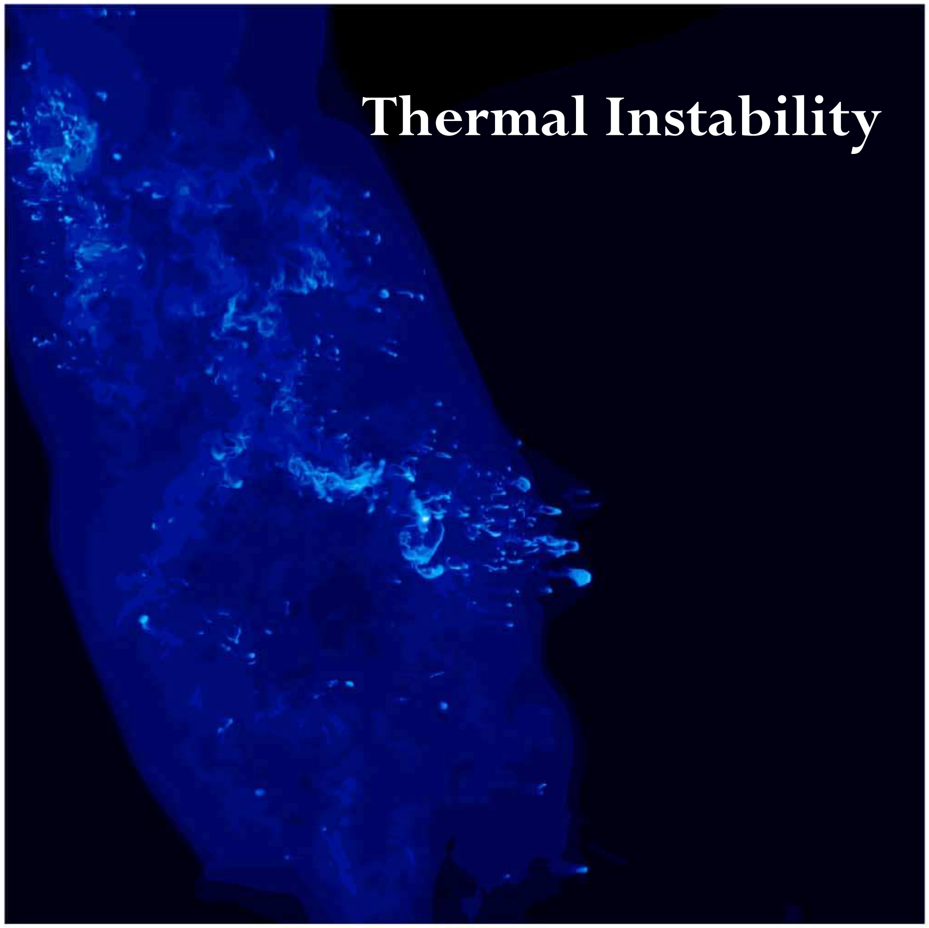
Heiles and Troland 2003: 25% of WNM (Wolfire) is in the thermally unstable range; 60% of HI is WNM with volume filling factor of ~1/2

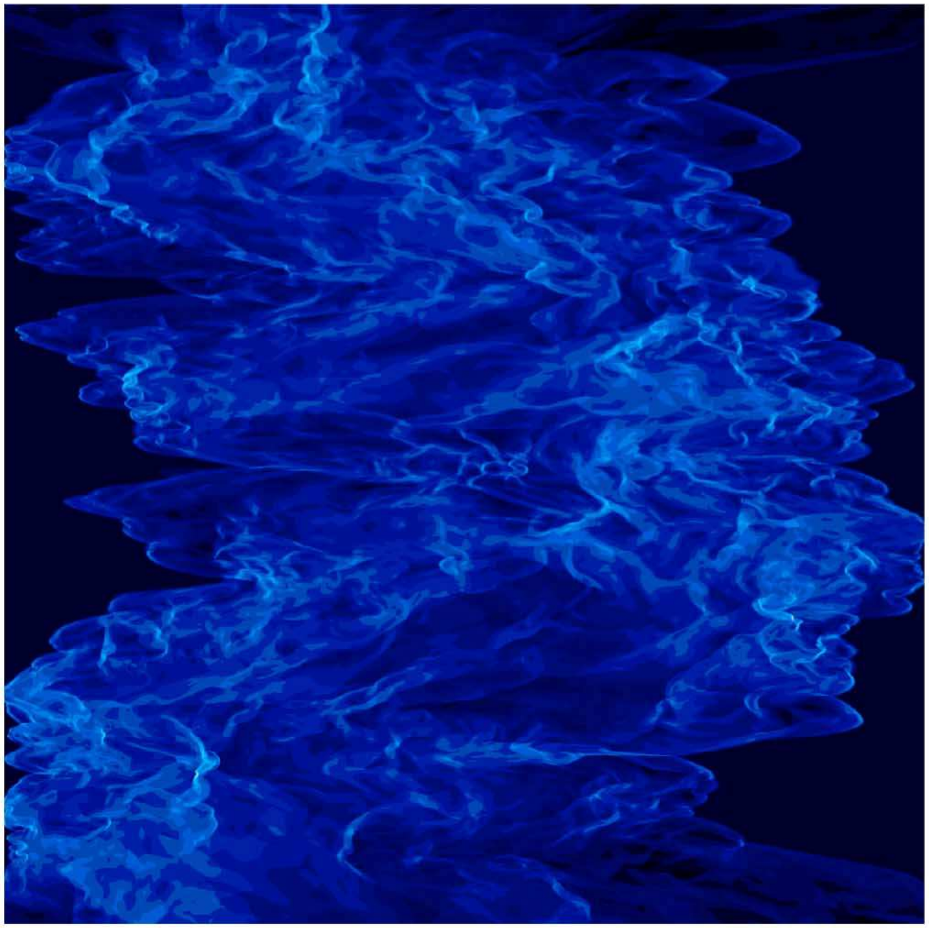


Begum +10: Broad HI absorption lines found with linewidths in the unstable range for WNM ($T_{k,max}$ < 1500 K)

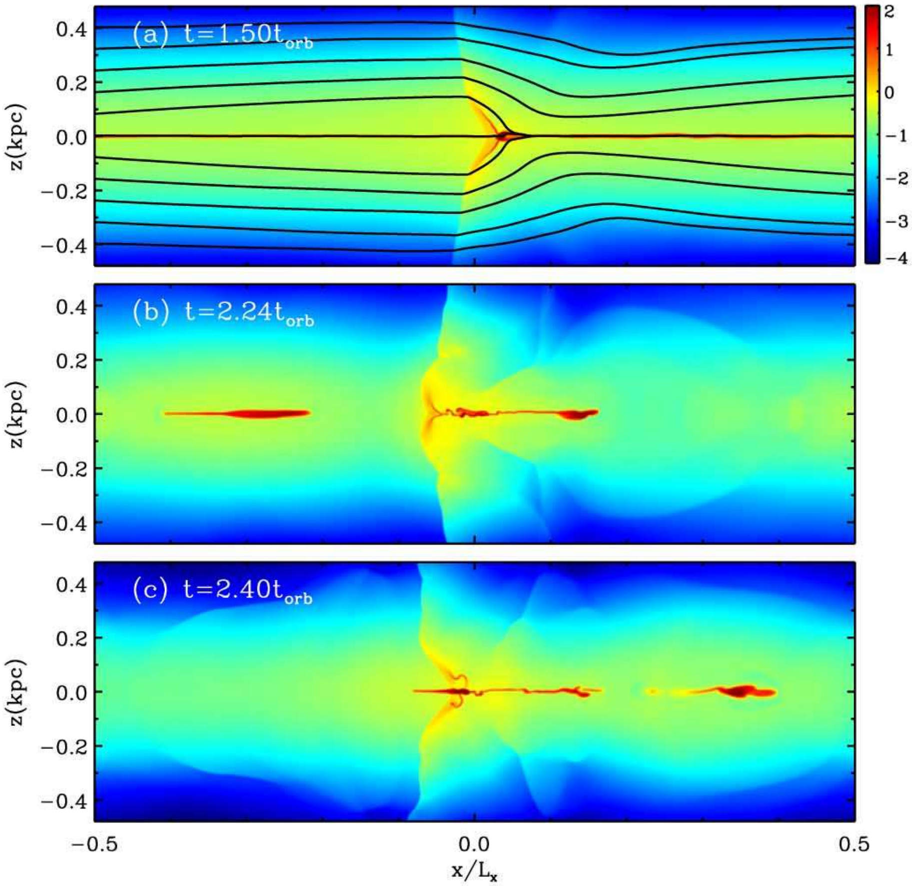
Concepts of Equilibrium

- Thermal/Mechanical equilibrium
  - thermal equilibrium determines cool/warm phase properties
    - heating/cooling timescales faster than kinematic (unless $L<0.01$ pc)
    - thermal instability at one P can form CNM/WNM phases in atomic gas

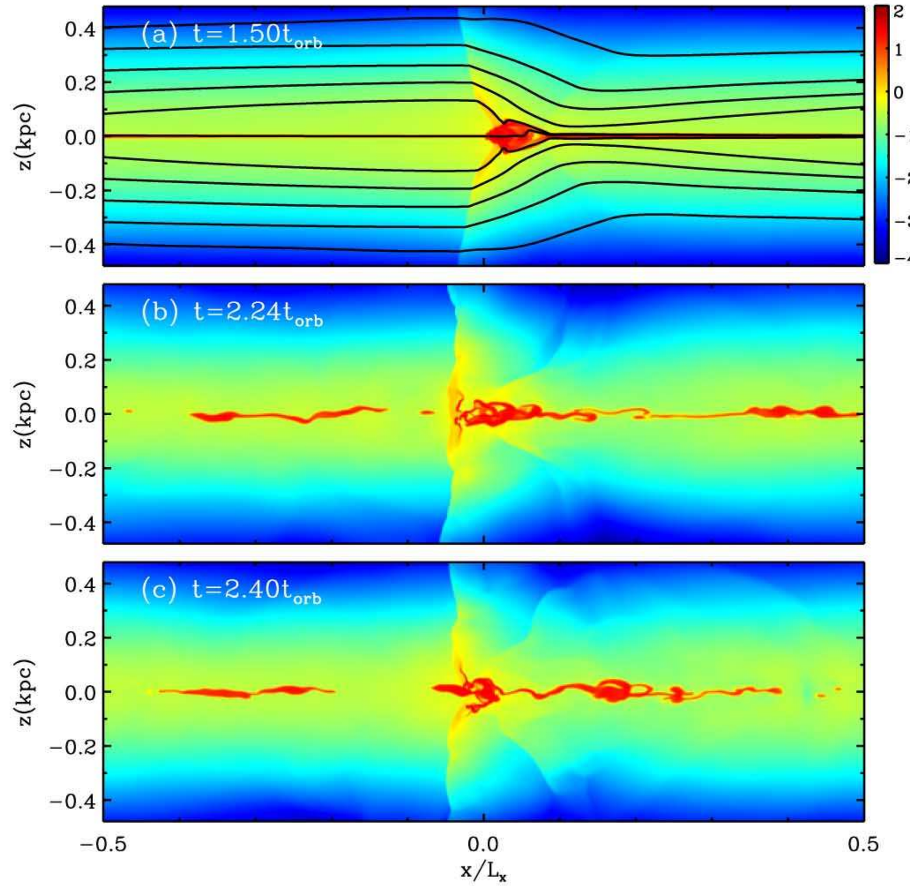




Audit & Hennebelle 2010: 3D converging flow (left) with two stable phases, (right) isothermal



self-gravitating with dense gas phase



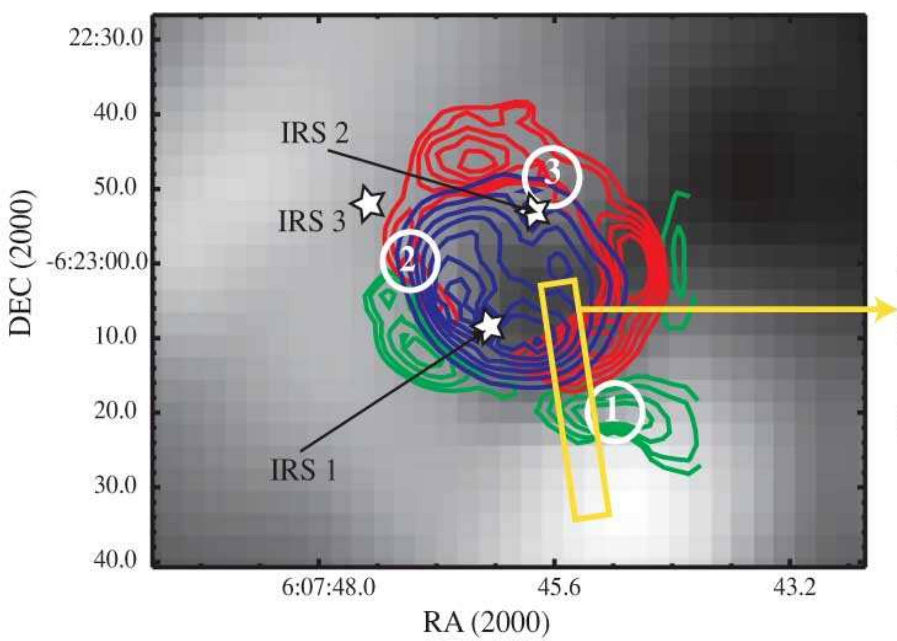
self-gravitating with density limited by a heating function that mimics SF

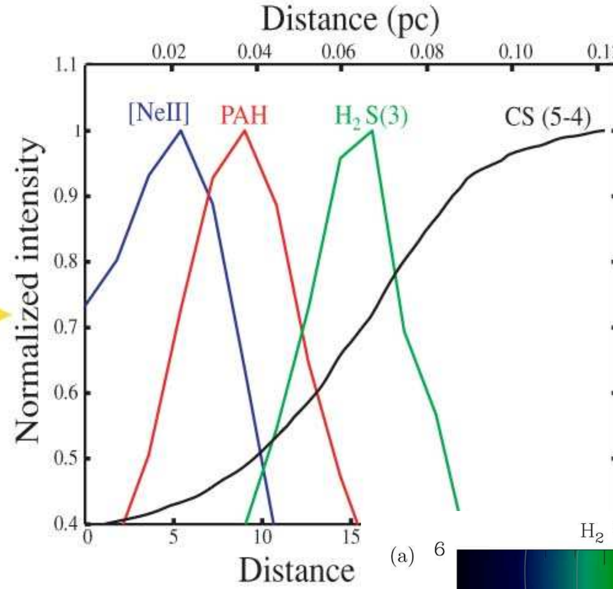
Kim, Kim & Ostriker 2010: Spiral shock in 2D with 2 thermal phases.

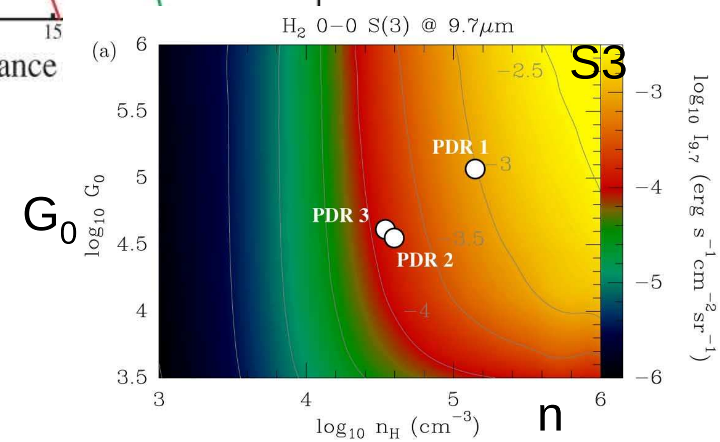
Shock triggers condensation of dense clouds by thermal instability. SF needed to break the clouds apart. In self-gravitating models, σ_{dense}~4-5 km/s, σ_{rare}~7 km/s

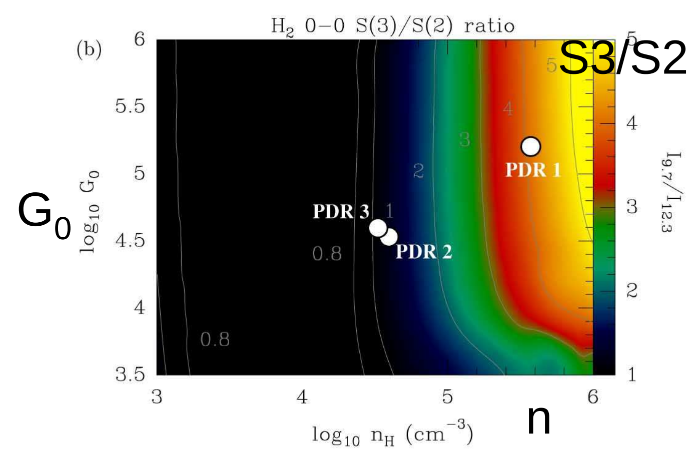
Concepts of Equilibrium

- Thermal/Mechanical equilibrium
  - thermal equilibrium determines cool/warm phase properties
    - heating/cooling timescales faster than kinematic
    - thermal instability at one P can form CNM/WNM phases in atomic gas
  - Photon Dominated Regions









Berne +09: PDRs around Mon R2.

H_2 S(3) and S(3)/S(2) ratios and $I_{6.2\mu}/I_{11.3\mu}$ ratio to give the PAH^+/PAH^0 ratio, which depends on $G_0T^{1/2}/n_e$

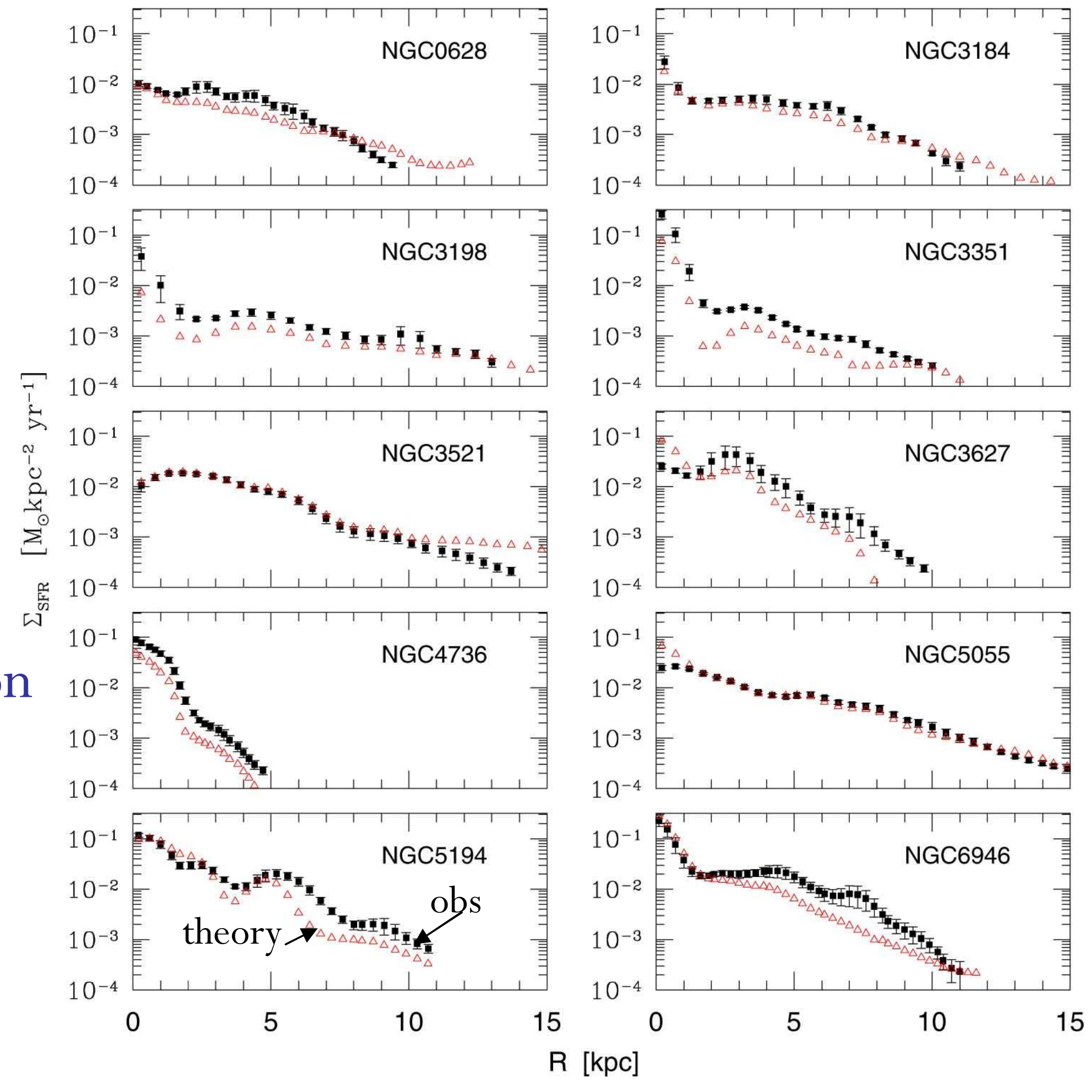
Concepts of Equilibrium

- Thermal/Mechanical equilibrium
  - thermal equilibrium determines cool/warm phase properties
    - heating/cooling timescales faster than kinematic
    - thermal instability at one P can form CNM/WNM phases in atomic gas
  - Photon Dominated Regions
  - GMC shielding, molecular fractions, empirical galactic SF laws…

Ostriker, McKee & Leroy 10 model for SFR assumes:

Diffuse gas column determined such that the weight of the diffuse ISM gives the required pressure for 2 stable phases with heating from star formation

Then SFR = all non-diffuse gas divided by a fixed time



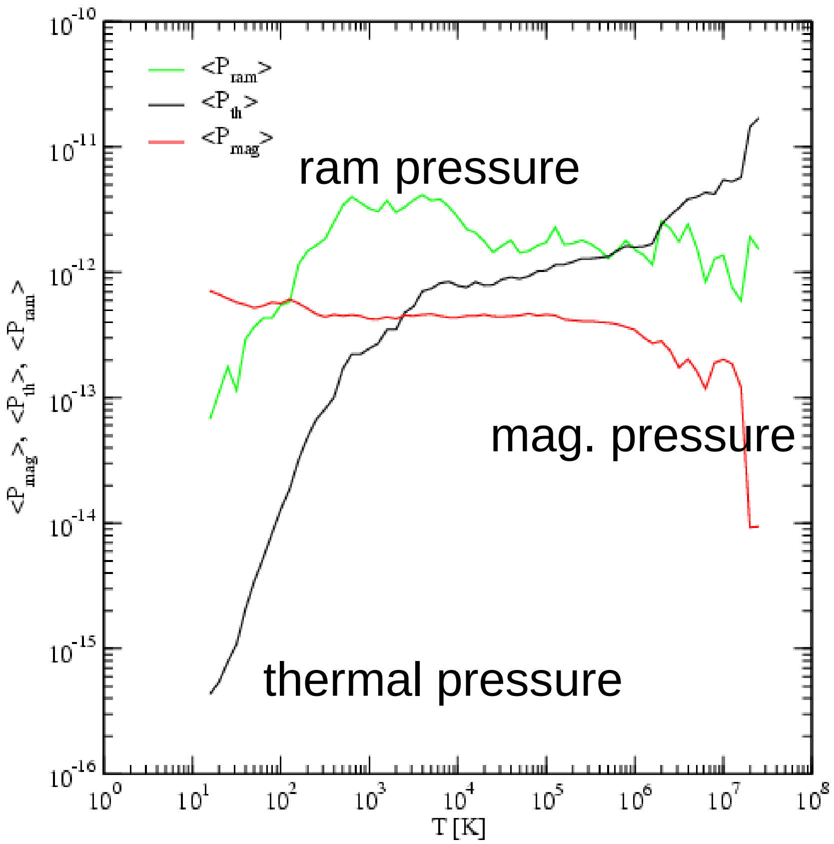
comparison to Leroy +08 observations

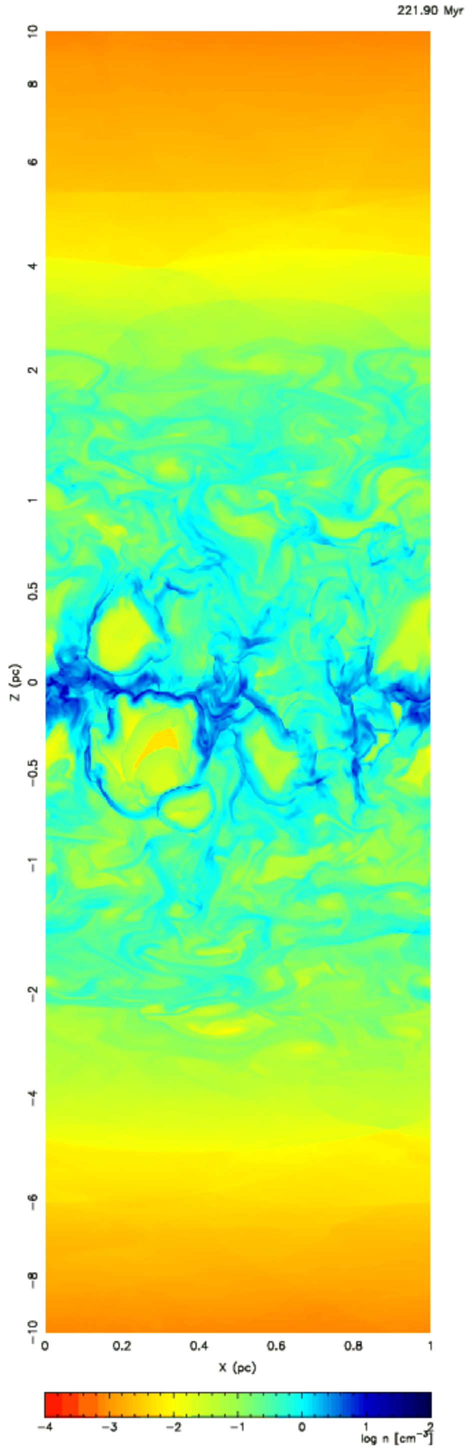
Concepts of Equilibrium

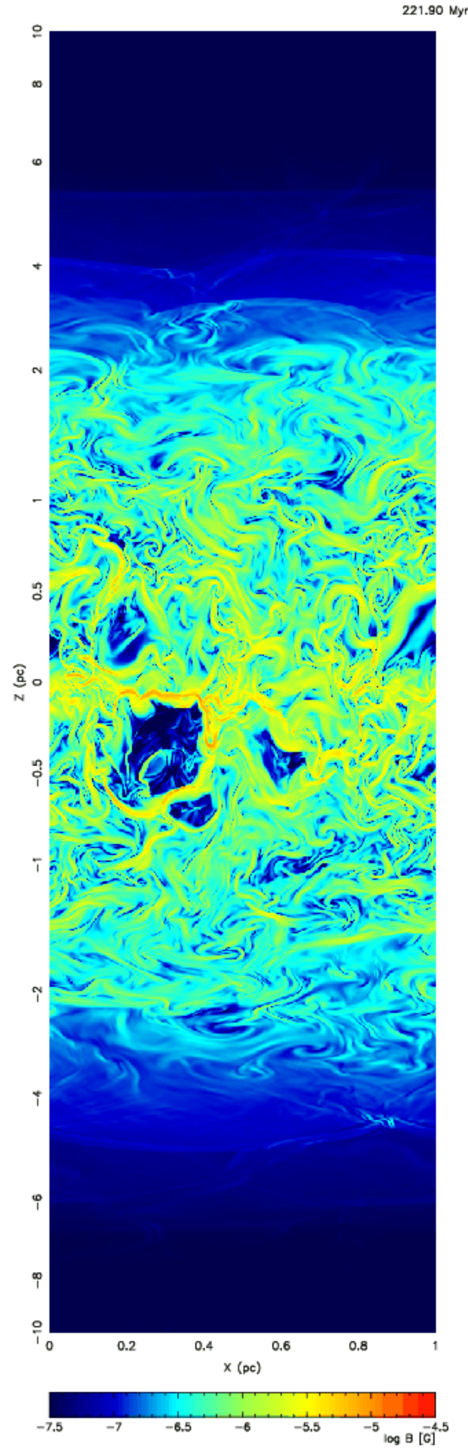
- Thermal/Mechanical equilibrium
  - thermal equilibrium determines cool/warm phase properties
    - heating/cooling timescales faster than kinematic
    - thermal instability at one P can form CNM/WNM phases in atomic gas
  - Photon Dominated Regions
  - GMC shielding, molecular fractions, empirical galactic SF laws…
  - ISM equilibrium on galactic scales from supernova stirring versus turbulence dissipation
    - turbulence and magnetism determine the galactic scale height

De Avillez & Breitschwerdt 05

Stirring from supernovae gives velocity dispersion and scale height.







ISM Energy Content

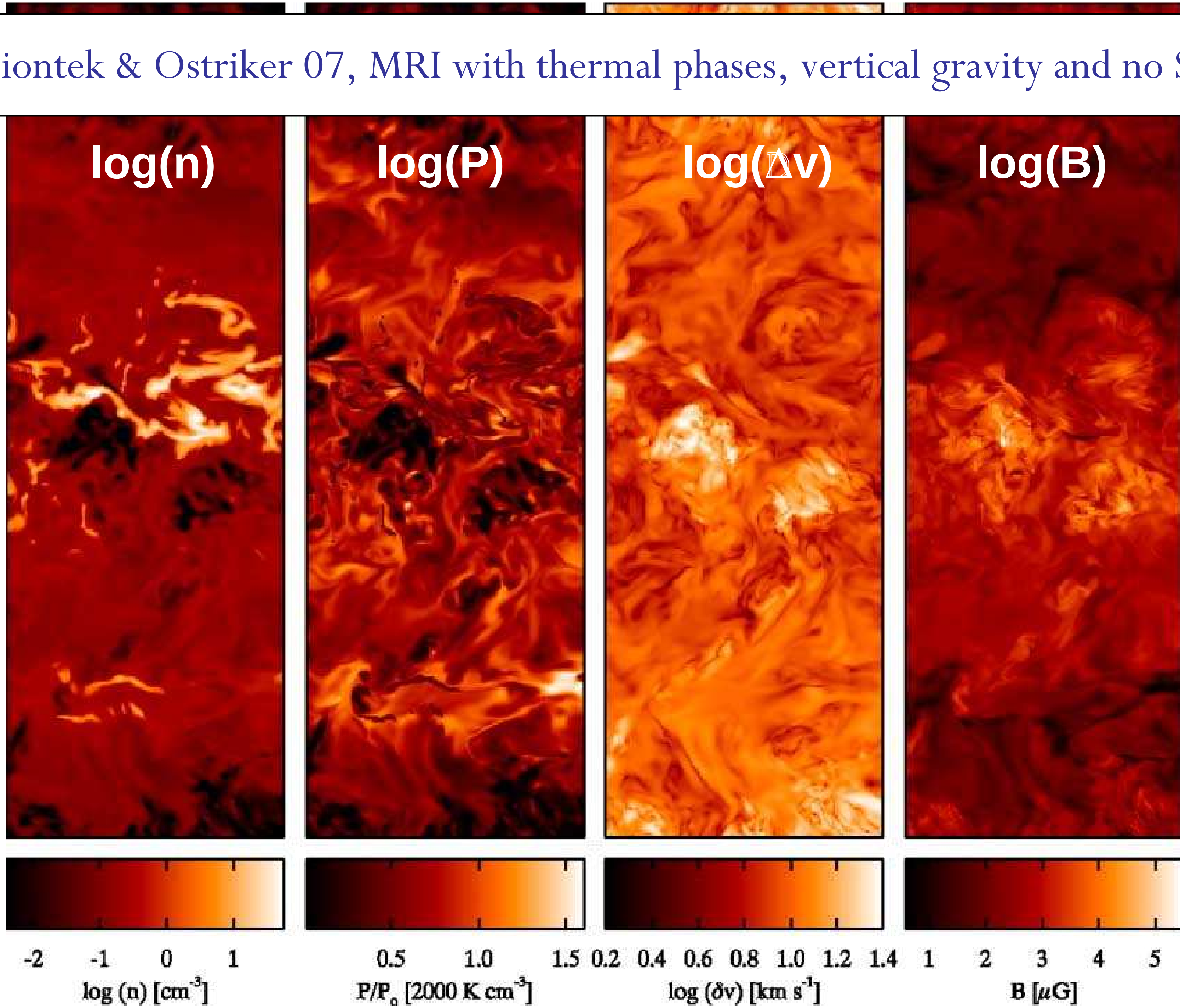
- Thermal ~ $1.5nk_BT$ ~ 3000 k_B (Jenkins & Tripp 01 value)
- Magnetic ~ $B^2/8\pi$ ~2100 k_B ($B=3\mu G$)
- Kinetic ~ $0.5\rho v^2$ ~ 3000 k_B (n=1, v=7 km/s)
- Cosmic Rays ~ 4800 k_B

  SUM ~ 13,000 k_B

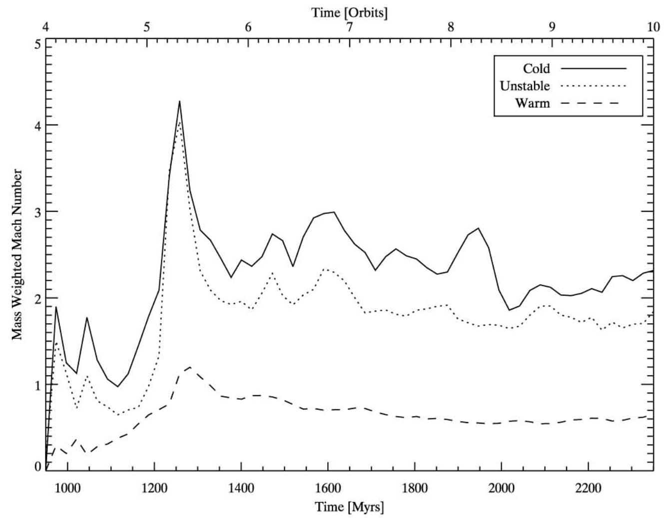
- Vertical gravity: $0.5\pi G\Sigma_{gas}(\Sigma_{gas}+\sigma_{gas}\Sigma_{stars}/\sigma_{stars})$ ~ 13,000 k_B

The summed ISM energy densities balance vertical gravity (Parker 1965)

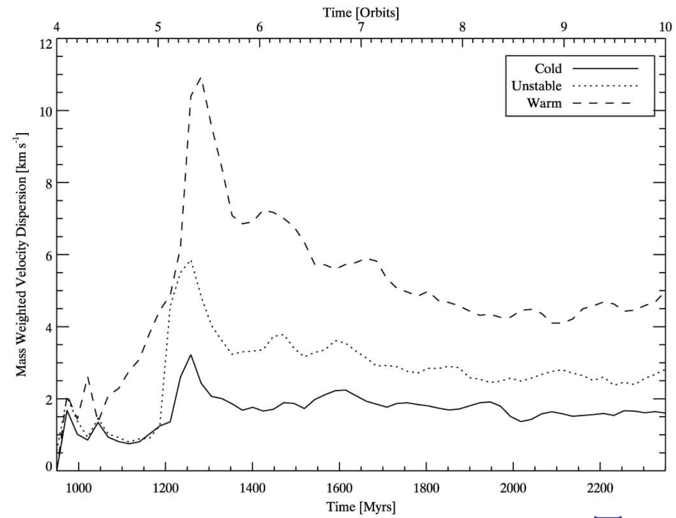
Piontek & Ostriker 07, MRI with thermal phases, vertical gravity and no SG



Mach No.
vs. Time



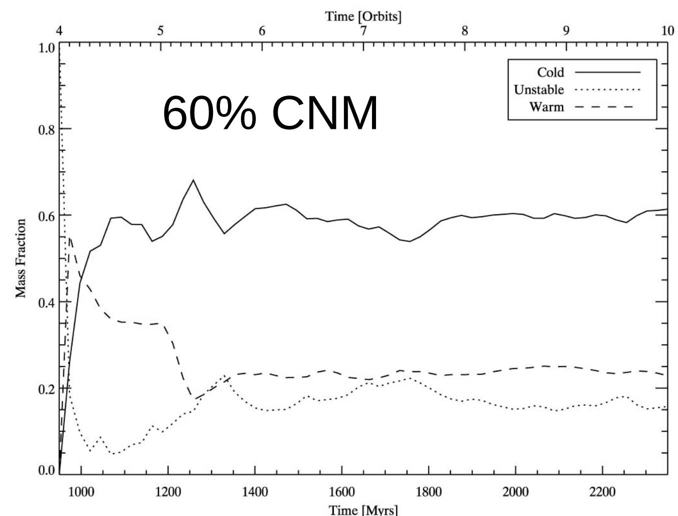
Time



Velo. Disp.
vs. Time

Time

MRI pumps turbulence from rotational energy and turbulence compression triggers thermal phase separation.



Mass
Fraction
vs. Time

Time

Piontek & Ostriker 07

ISM Energy Content

- Thermal ~ $1.5nk_BT$ ~ 3000 k_B
- Magnetic ~ $B^2/8\pi$ ~2100 k_B ($B=3\mu G$)
- Kinetic ~ $0.5\rho v^2$ ~ 3000 k_B (n=1, v=7 km/s)
- Cosmic Rays ~ 4800 k_B

  SUM ~ 13,000 k_B

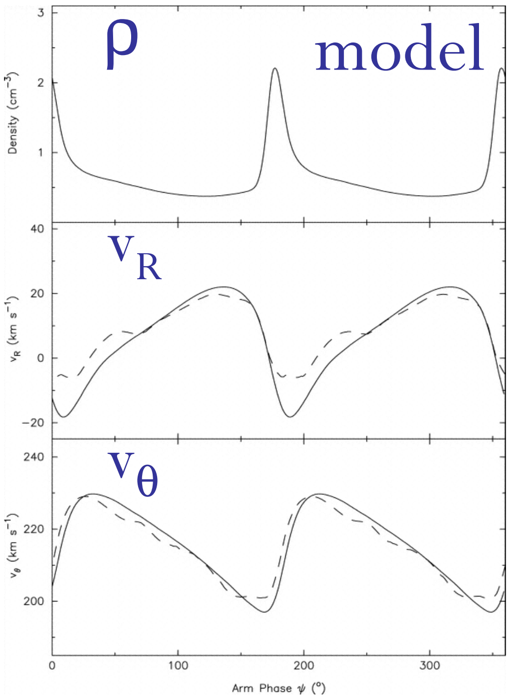
- Vertical gravity: $0.5\pi G\Sigma_{gas}(\Sigma_{gas}+\sigma_{gas}\Sigma_{stars}/\sigma_{stars})$ ~ 13,000 k_B

The summed ISM energy densities balance vertical gravity (Parker 1965)

- Rotation ~ $0.5\rho V^2$ ~2,900,000 k_B (n=1, V=220 km/s)

  (Potentially enormous source of ISM energy)

In spiral galaxies,
ISM dynamics can be
dominated by the spirals

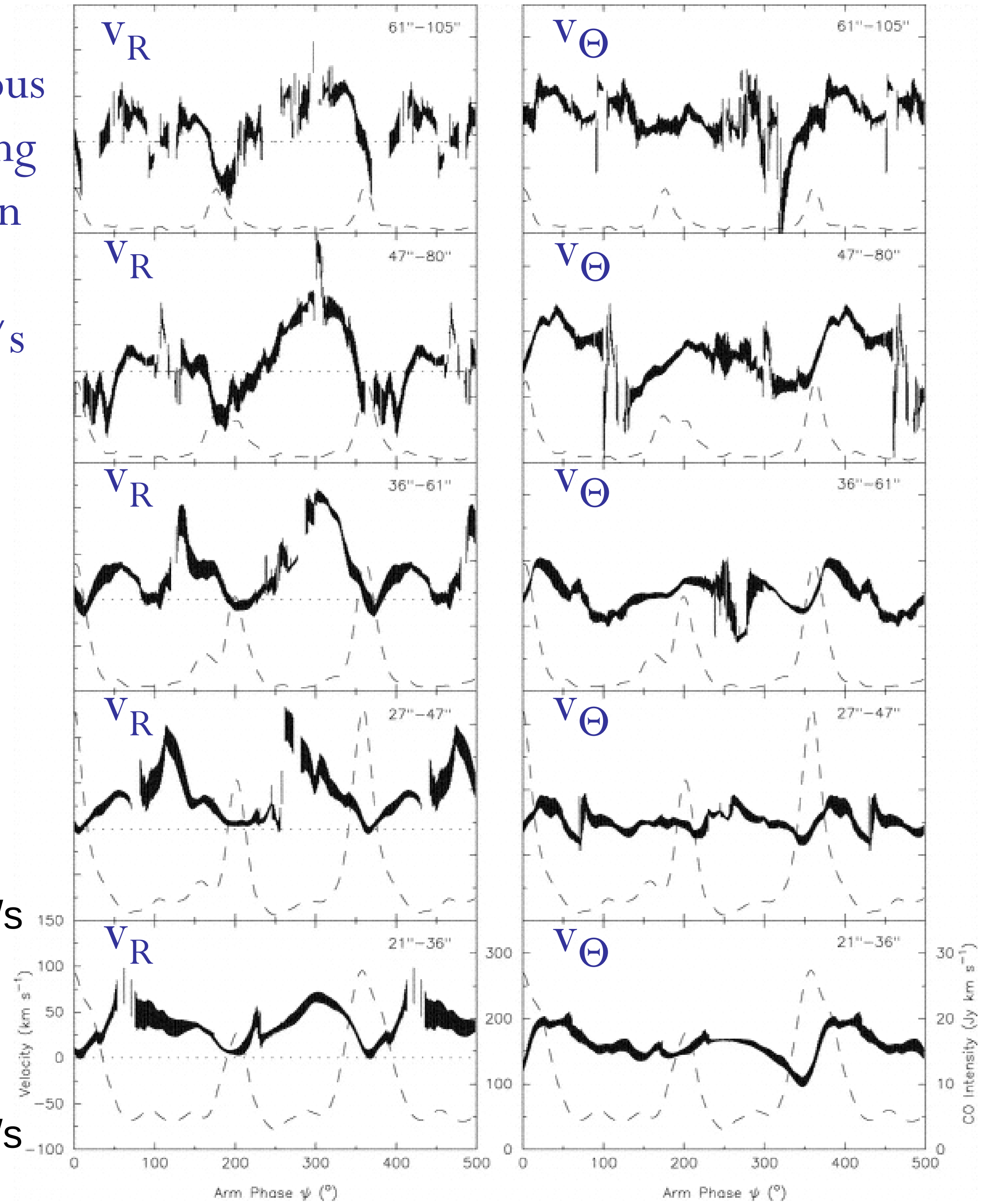


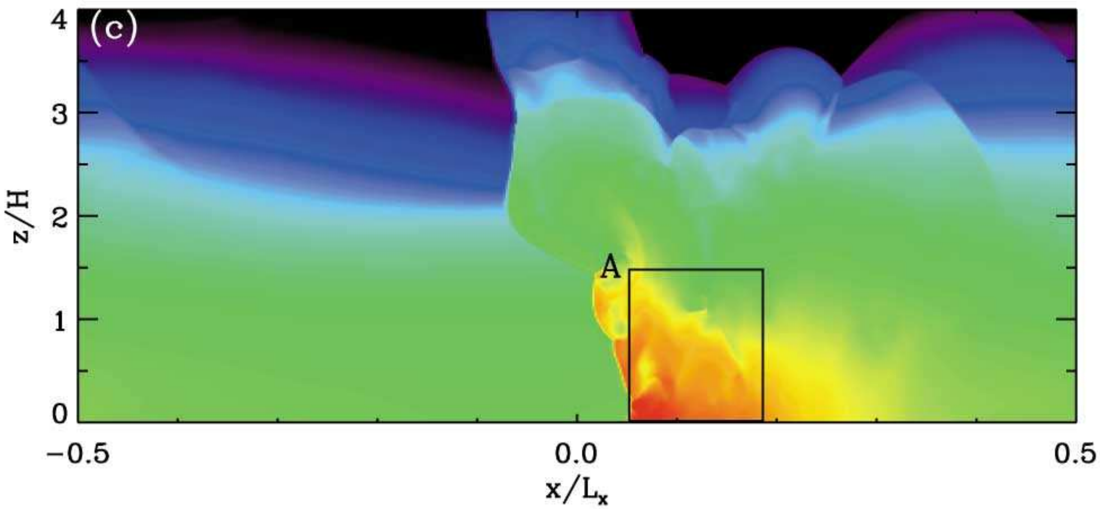
Enormous streaming speeds in M51 ~ 80 km/s

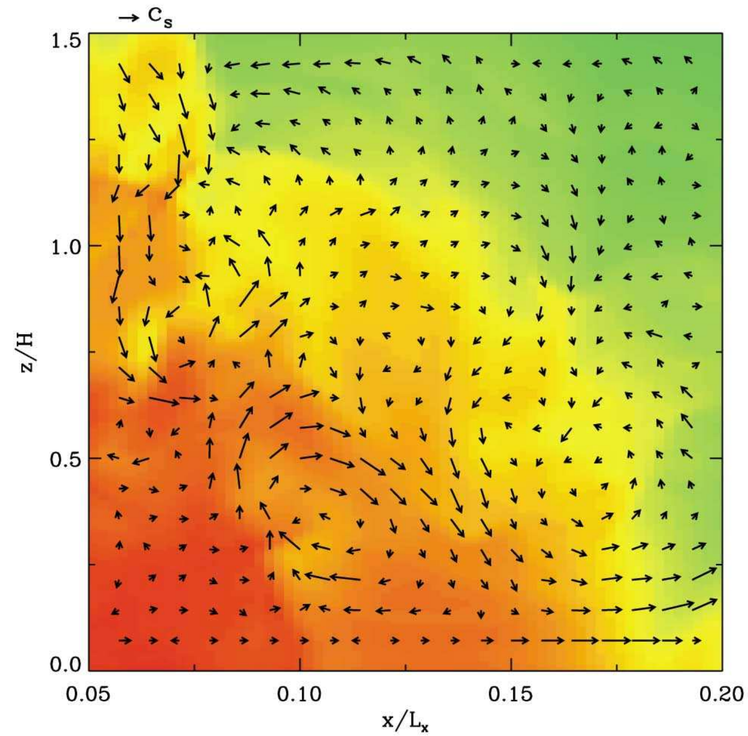
Shetty et al. 07

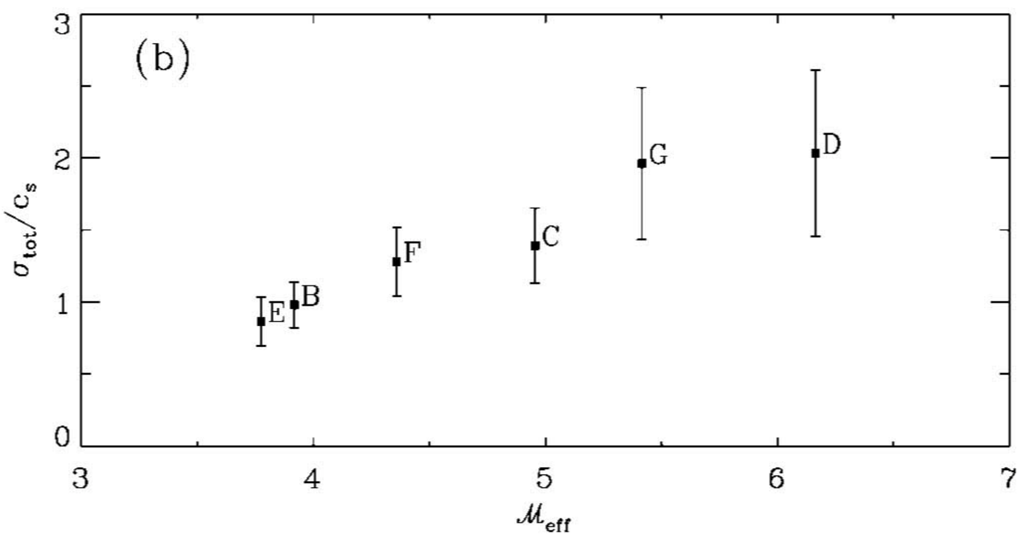
150 km/s

-100 km/s

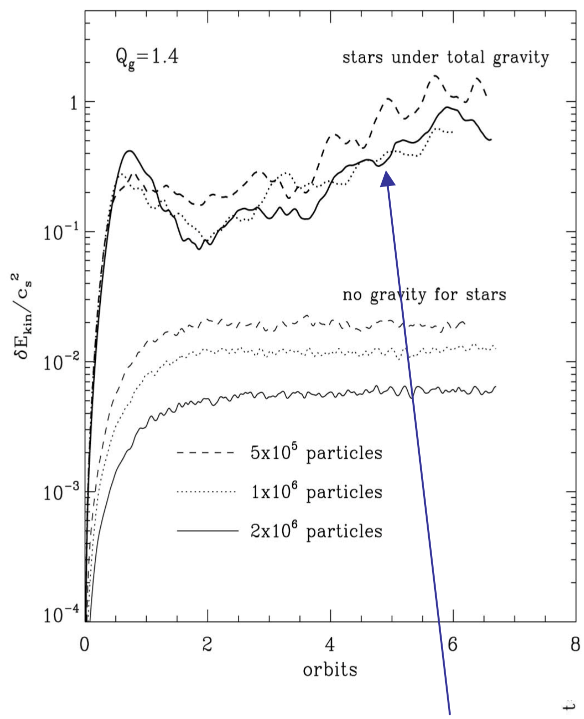




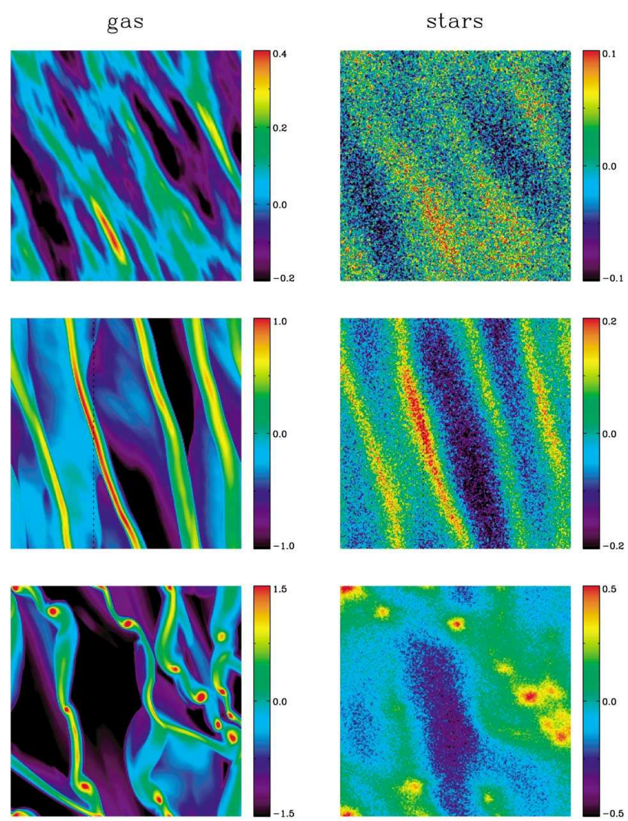




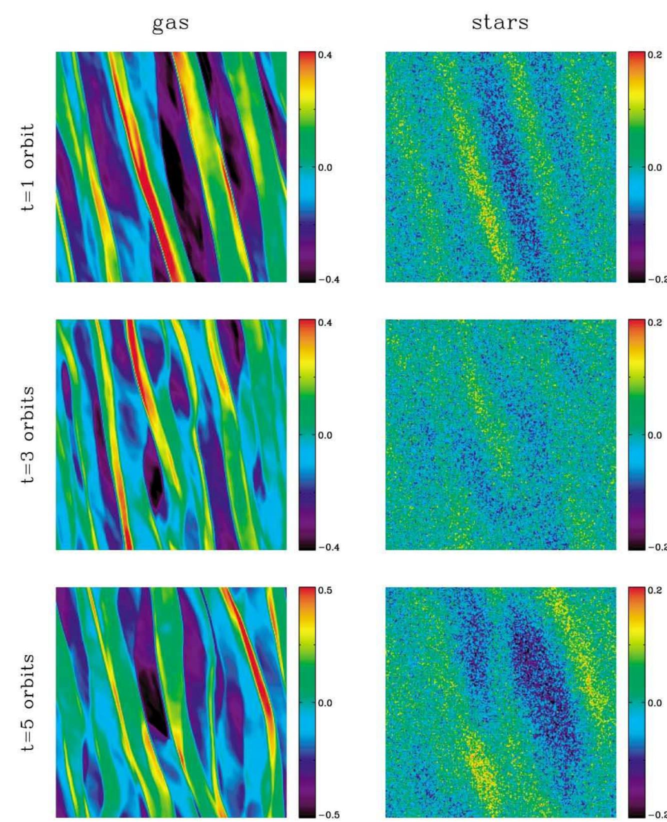
Kim, Kim & Ostriker 06: Flapping in spiral shocks generates turbulence



Turbulent Mach number increases with time



Q_{gas}=1: clouds form at intersecting spirals



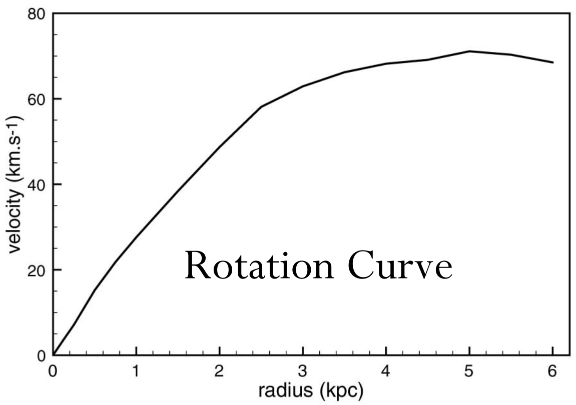
Q_{gas}=1.4

Kim & Ostriker 07: 2D star+gas self-gravitating simulations showing unstable growth of gas spirals at Q_{gas}<1.4 (Q_s=2.1) and turbulence driving at Q_{gas}>1.4

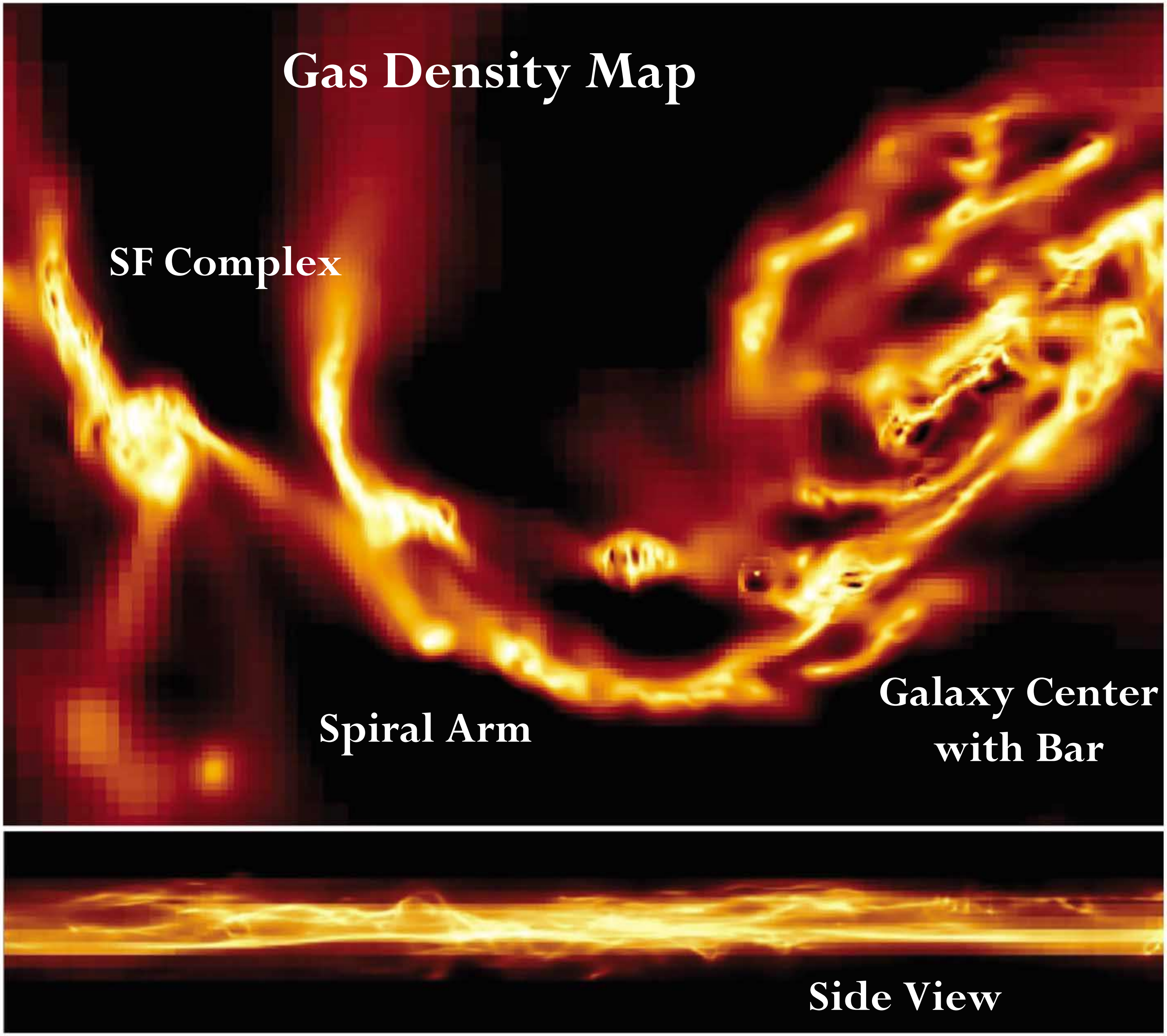
"spiral chaos" – Toomre

Bournaud +10 LMC Model

- AMR simulation of an LMC-size galaxy with cell size down to 0.8 pc
- Gas EoS with a equilibrium Temperature-Density relation
- self-gravity
- stars and DM represented by particles
  - $4\text{x}10^6$ for disk, $4\text{x}10^5$ for bulge, $4\text{x}10^6$ for DM halo
  - Q_{star}=1.5 forms bar



- Feedback from SF
  - threshold for SF = 5000 atoms/cm^3
  - above threshold: SFR = 10% of gas /free fall time
  - 20% of the stellar mass explodes as SNe.
  - In a SN, 10% of 10^{51}erg is injected into gas as radial
    - velocity kick around SN within radius of 3 pc
- Initial conditions: Thermally stable WNM gas with Q_{gas}=1-1.5


Gas Density Map
SF Complex
Spiral Arm
Galaxy Center
with Bar
Side View

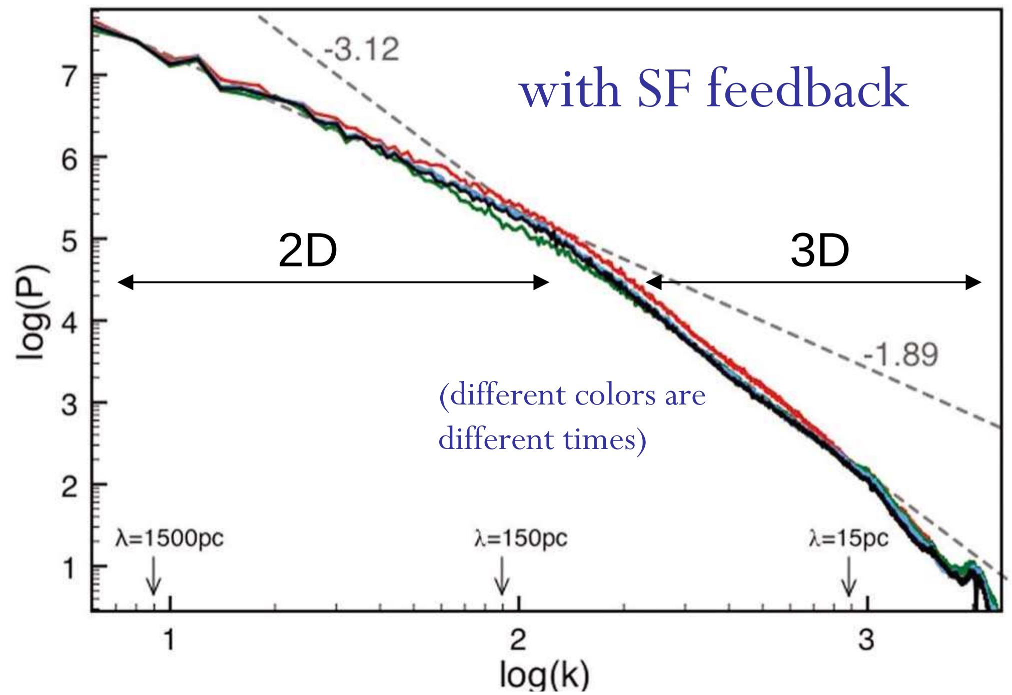
Results:

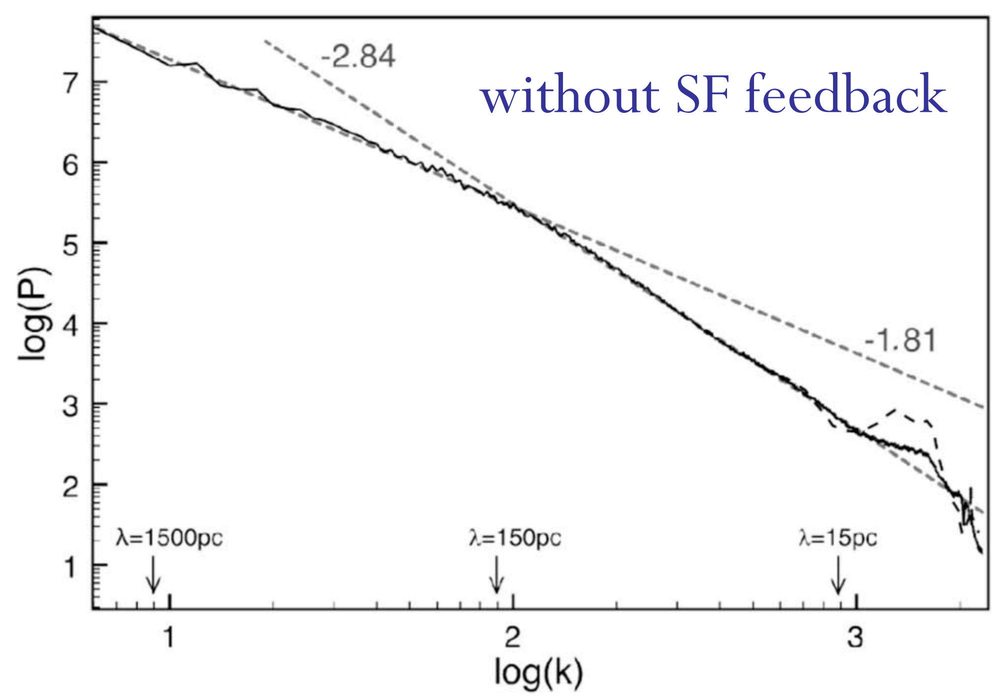
Self-gravity and star formation drive turbulence which is 3D at small scales and 2D at large scales.

Gravitational energy is from local collapse and streaming motions in spiral instabilities

Driving length ~ $1/k_{Jeans} \sim \sigma^2/\pi G\Sigma$ which is also the disk thickness

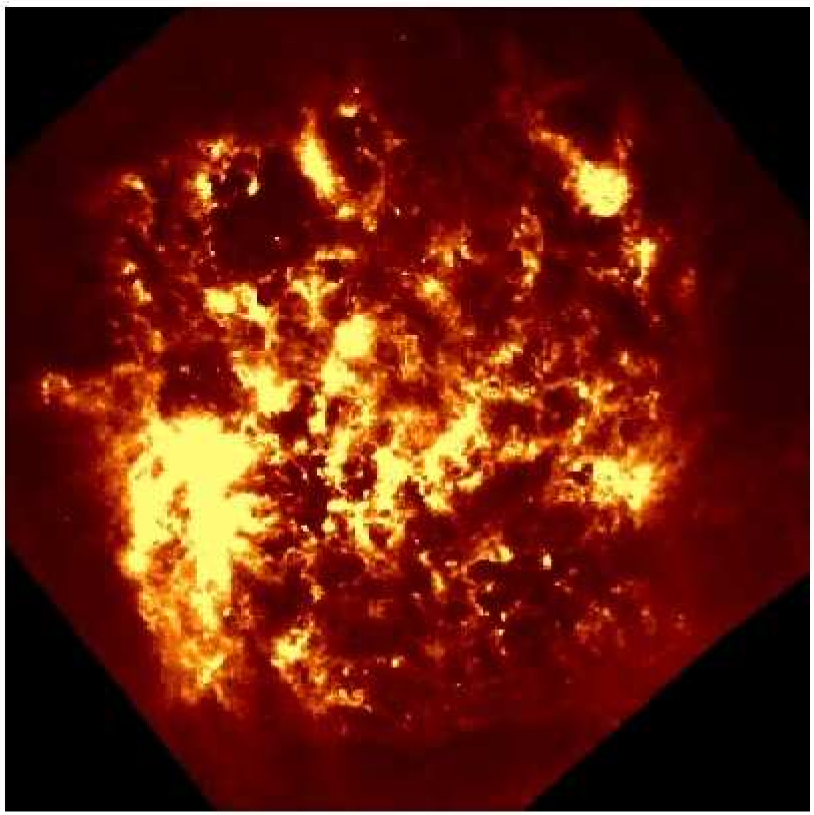
Feedback from star formation does not affect the power spectrum or the velocity dispersion much





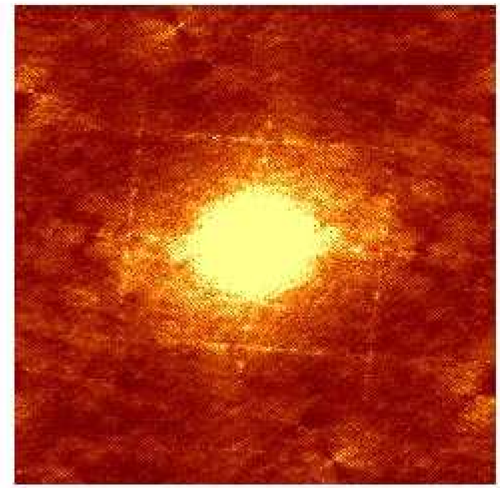
Power spectrum of whole LMC galaxy

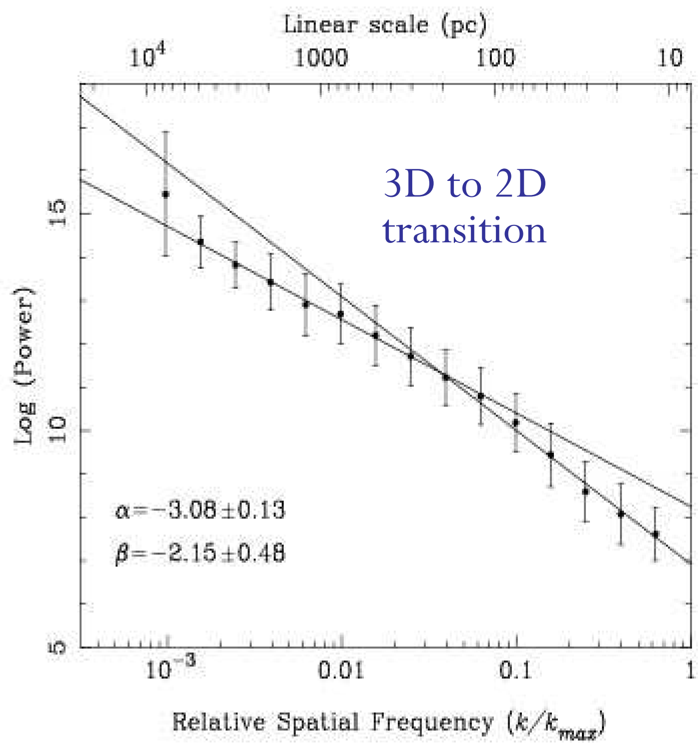
LMC – 160 microns



8.16 degrees

Fourier Transform

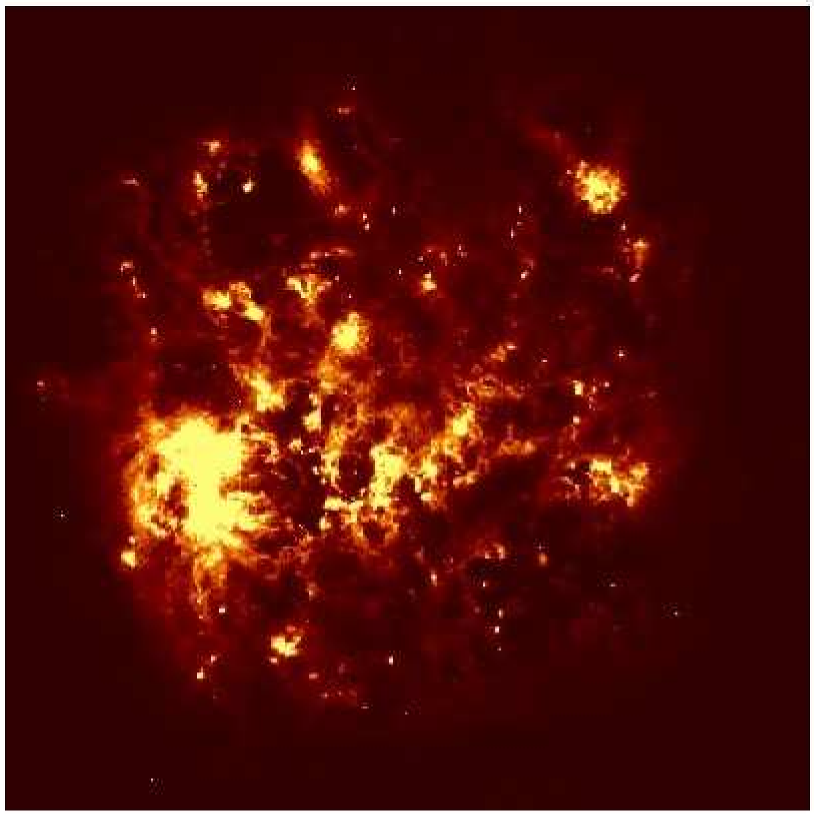




Block +10

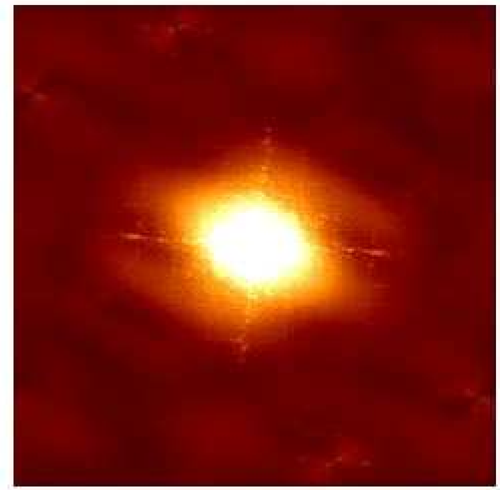
Power spectrum of whole LMC galaxy

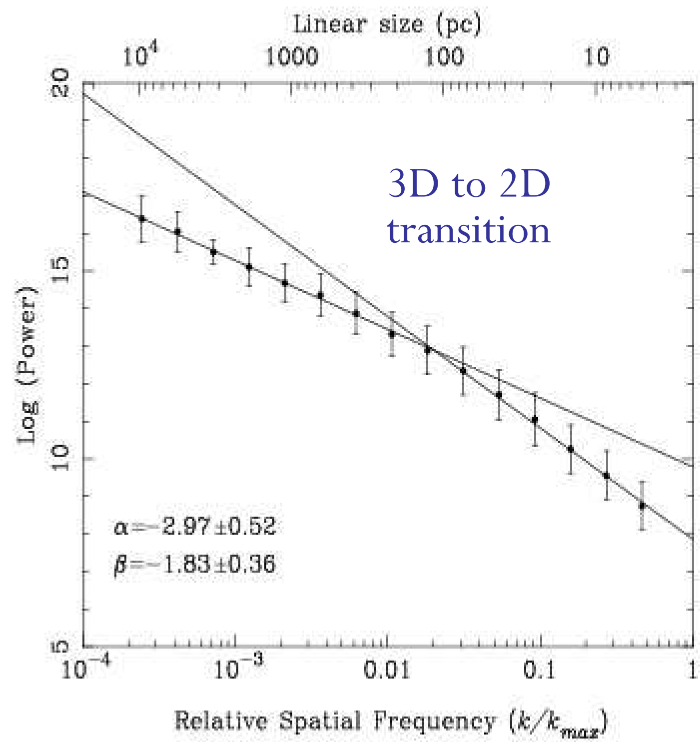
LMC – 70 microns



|← **8.16 degrees** →|

Fourier Transform

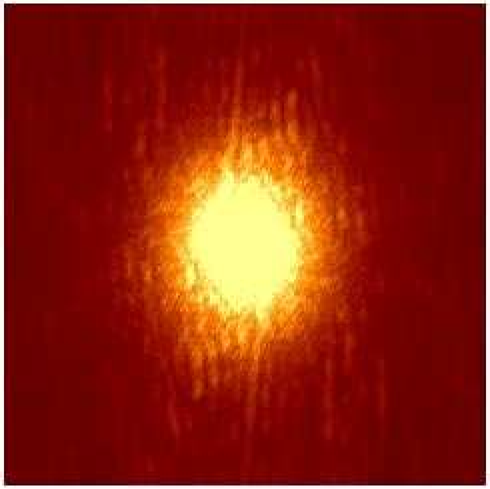




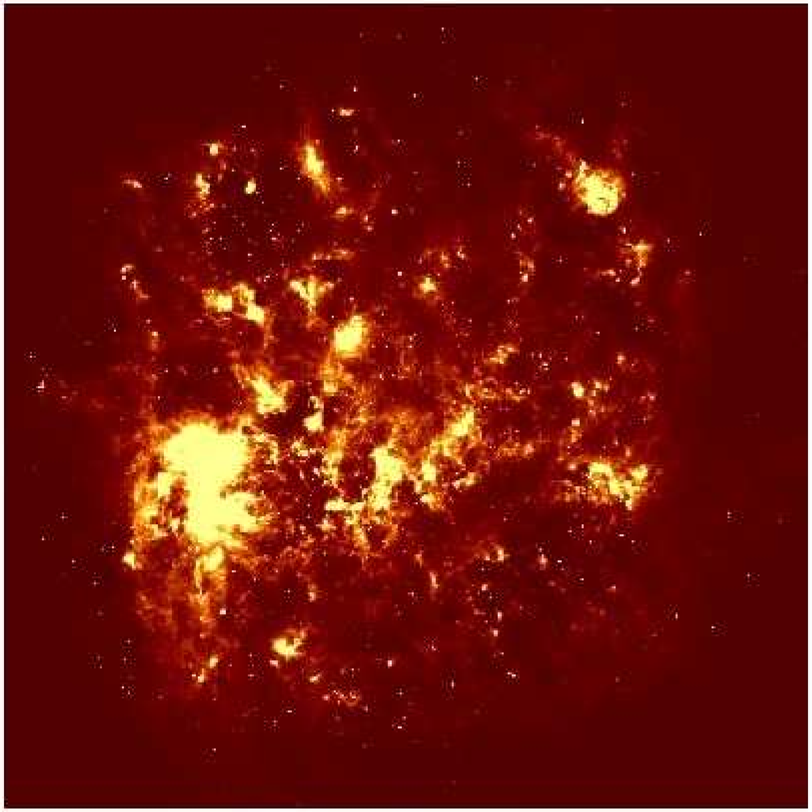
Block +10

Power spectrum of whole LMC galaxy

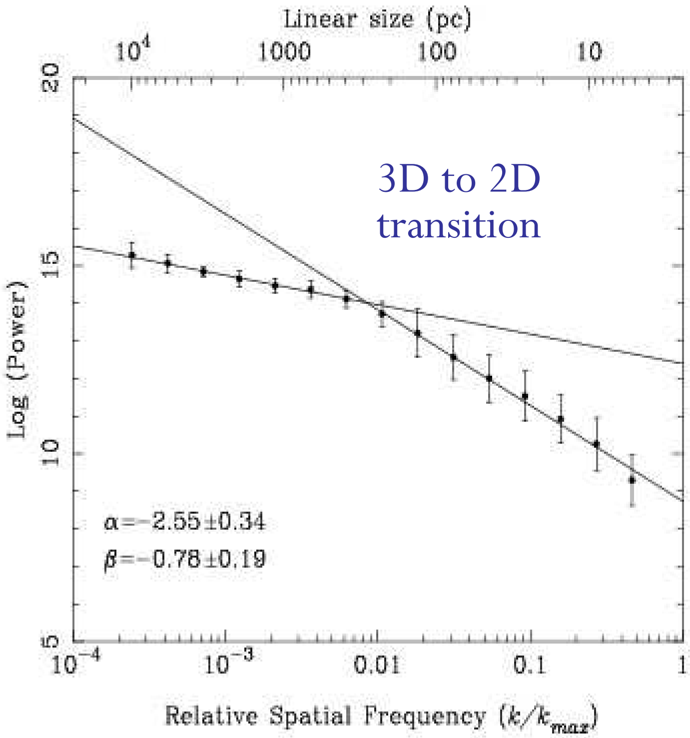
Fourier Transform



LMC – 24 microns

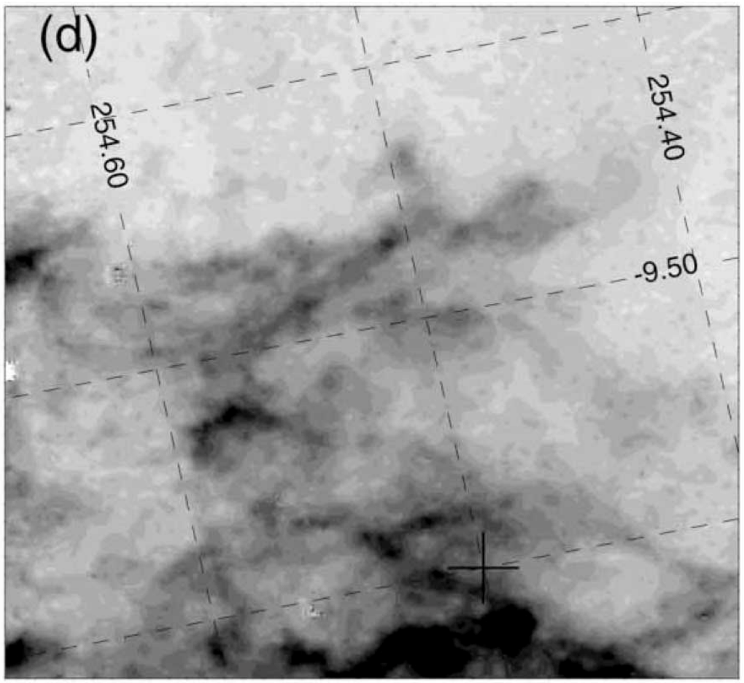


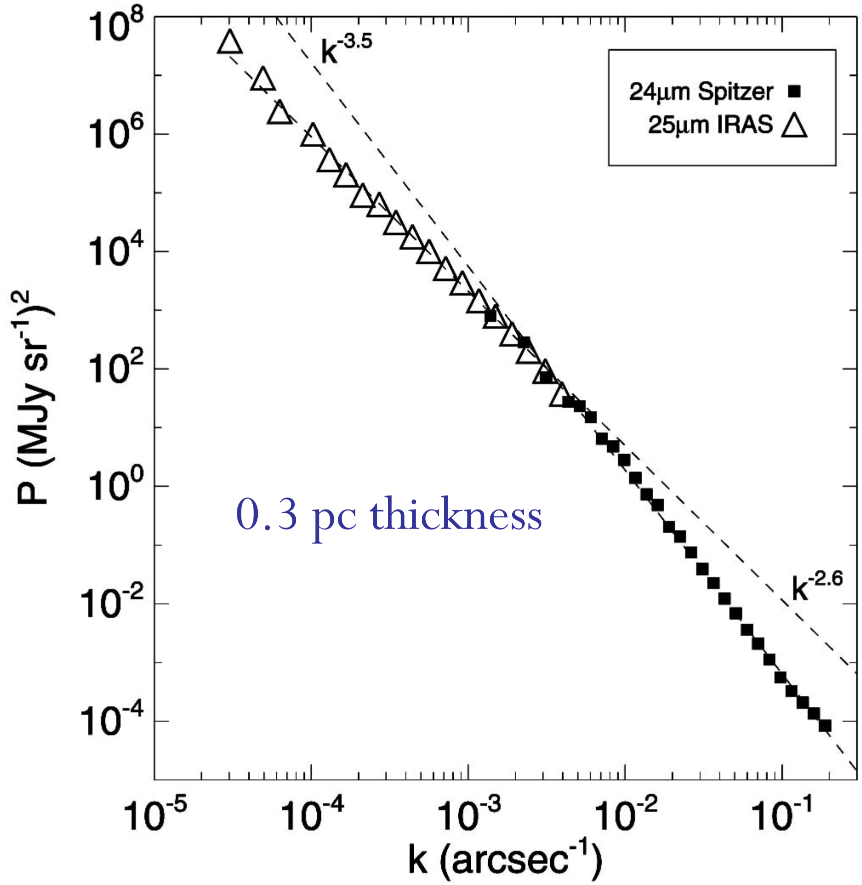
|← **8.16 degrees** →|

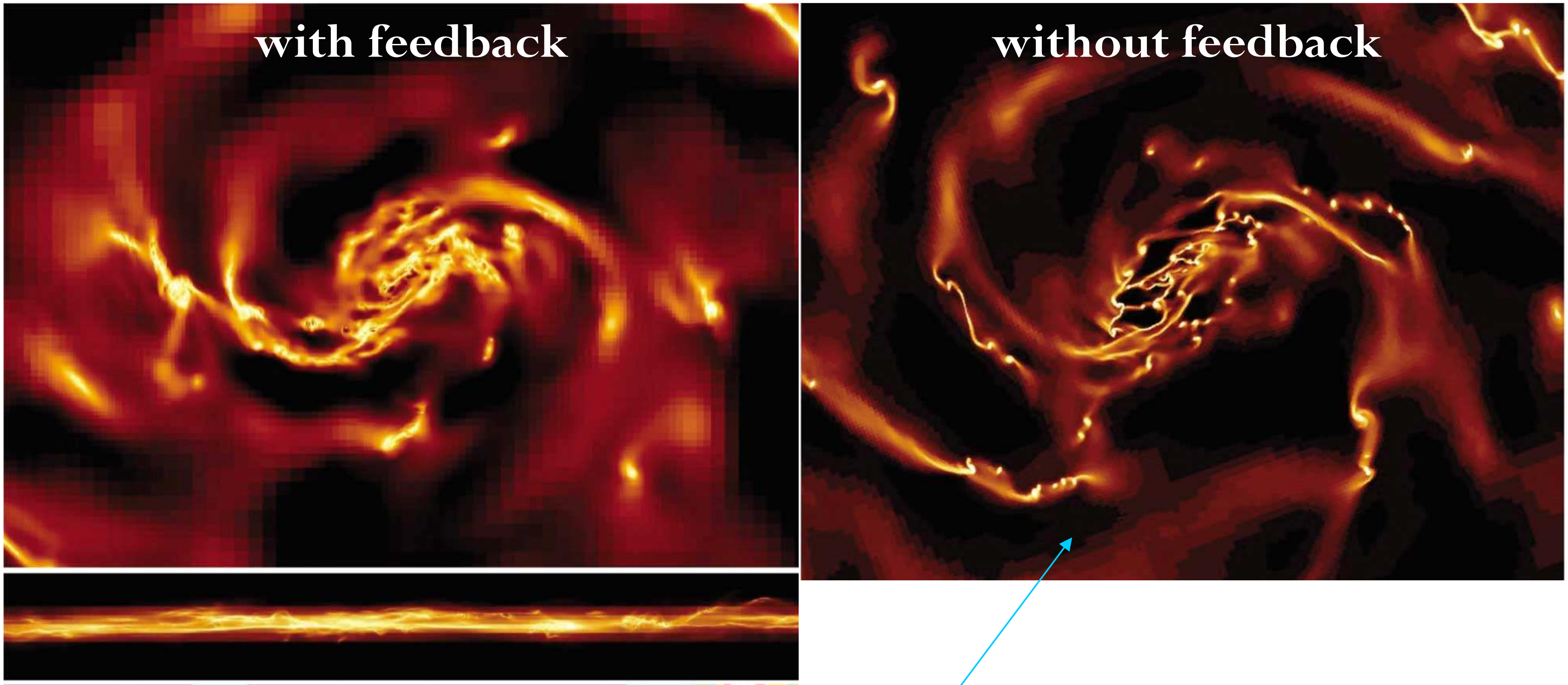


Block +10

Bent Power Spectrum
also found for molecular clouds
near the Gum nebula (Ingalls +04)



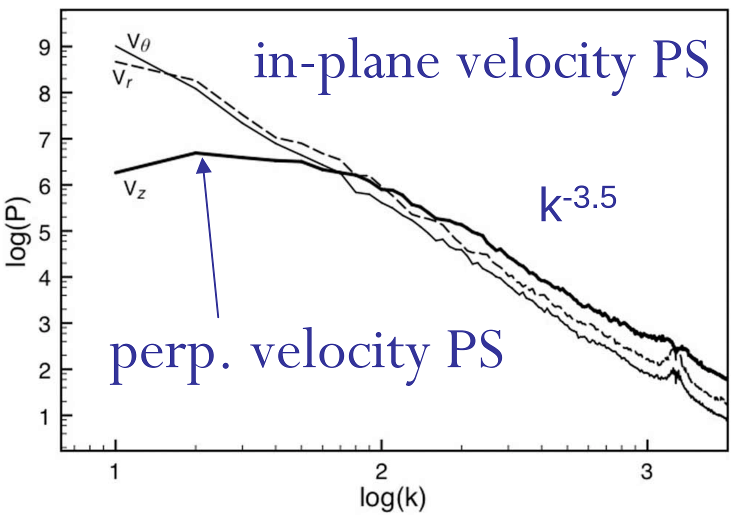




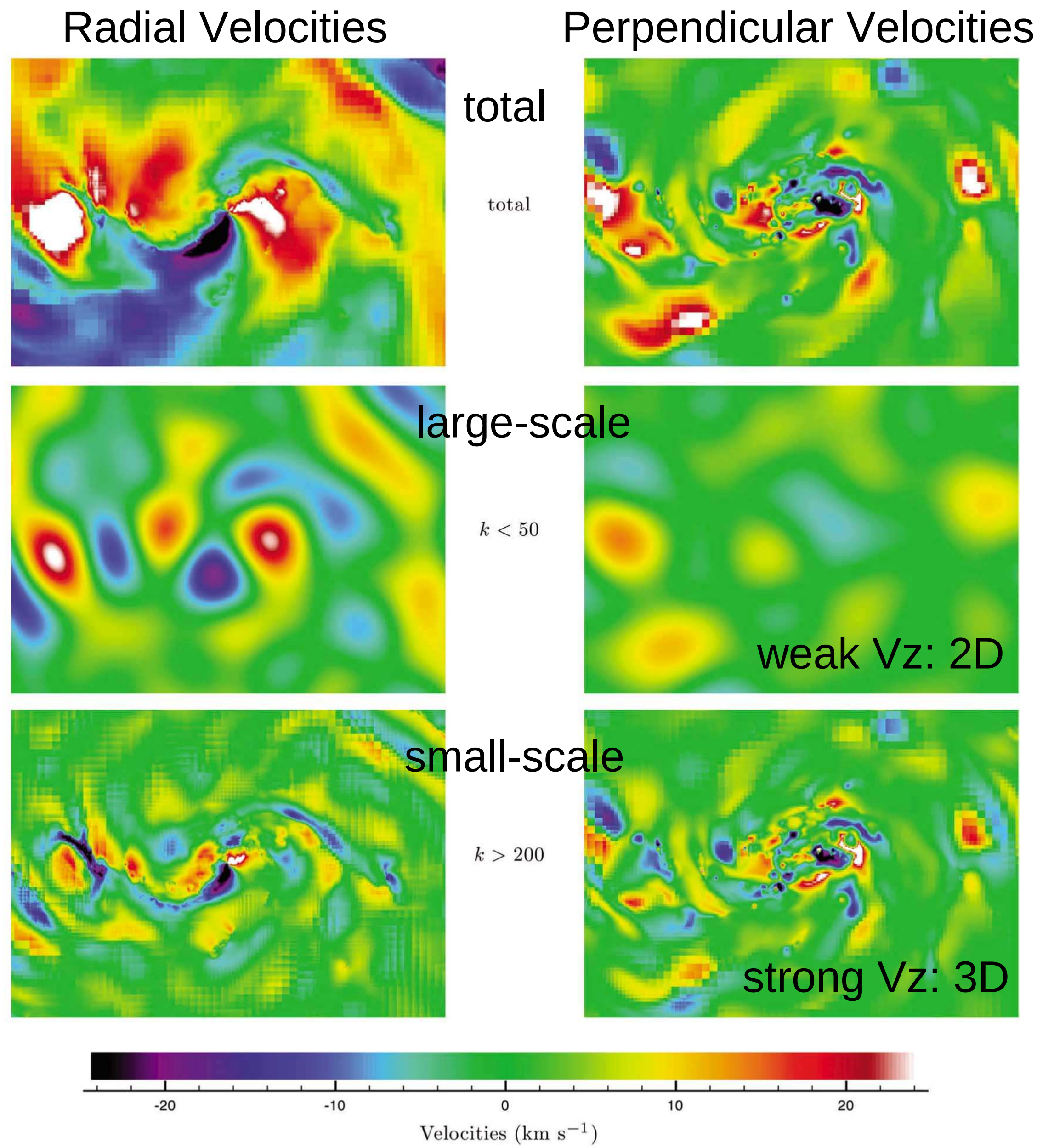
Without feedback, the cloud density increases without limit.

The mass-weighted 1D dispersion for all gas denser than 1 cm^{-3} before the clouds become compact, averaged over 3 separate timesteps is:

Gravity only: 8.13 km/s, Gravity + feedback: 8.4 km/s



Velocity power spectra for the three separate components, Vr , Vθ , and Vz



Mass-weighted velocities along the line of sight: Vr (left), Vz (right).

Large-scale motions are 2D, small scale motions are 3D

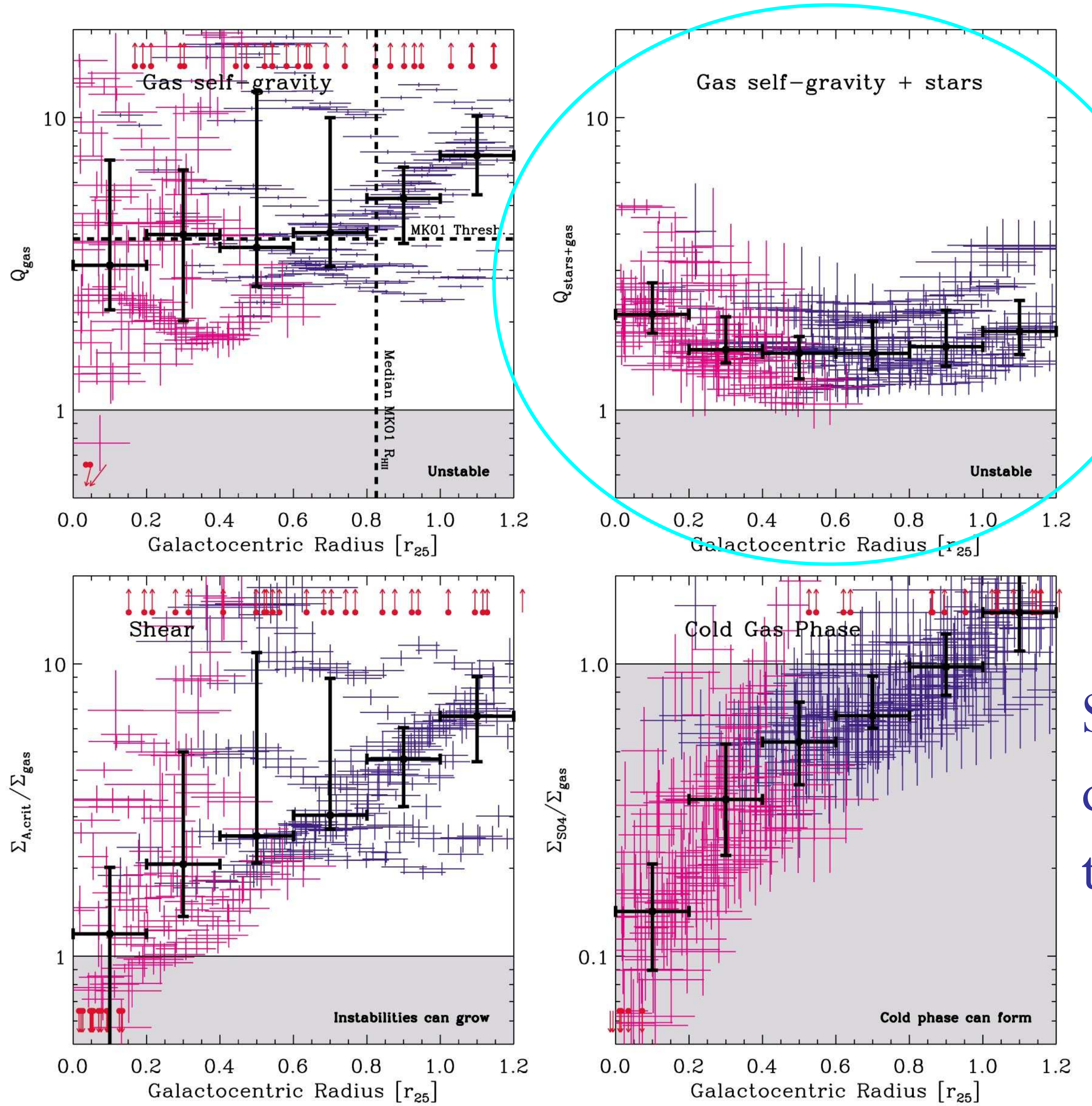
Sum: Gravity-Driven Turbulence in Galaxies

- Galaxies tap rotational energy via spiral arms
  - direct collapse energy + streaming/shock energy from relative gas and star motions
- Gravitational energy is long-range
  - in a disk, gravitational acceleration in-plane ~ $2\pi G\Sigma$, independent of distance
- Stellar energy is short-range, and used to lift gas out of deep potential wells (dense clouds)
  - stellar power can be much larger than disk self-gravity power but little stellar power reaches the large scale
- Gravity also drives motions inside the dense clouds ($L < 1/k_{Jeans}$)
- ISM dispersion from $Q_{Toomre} \sim \sigma\kappa/\pi G\Sigma \sim 1.5\text{-}2$, so $\sigma \sim 1.5\pi G\Sigma/\kappa$ and the scale height of the gas is $\sim 1/k_{Jeans}$

Qgas

Spirals

Shear threshold (k→A)



Rafikov 01 star+gas threshold

Schaye 04 cold phase threshold

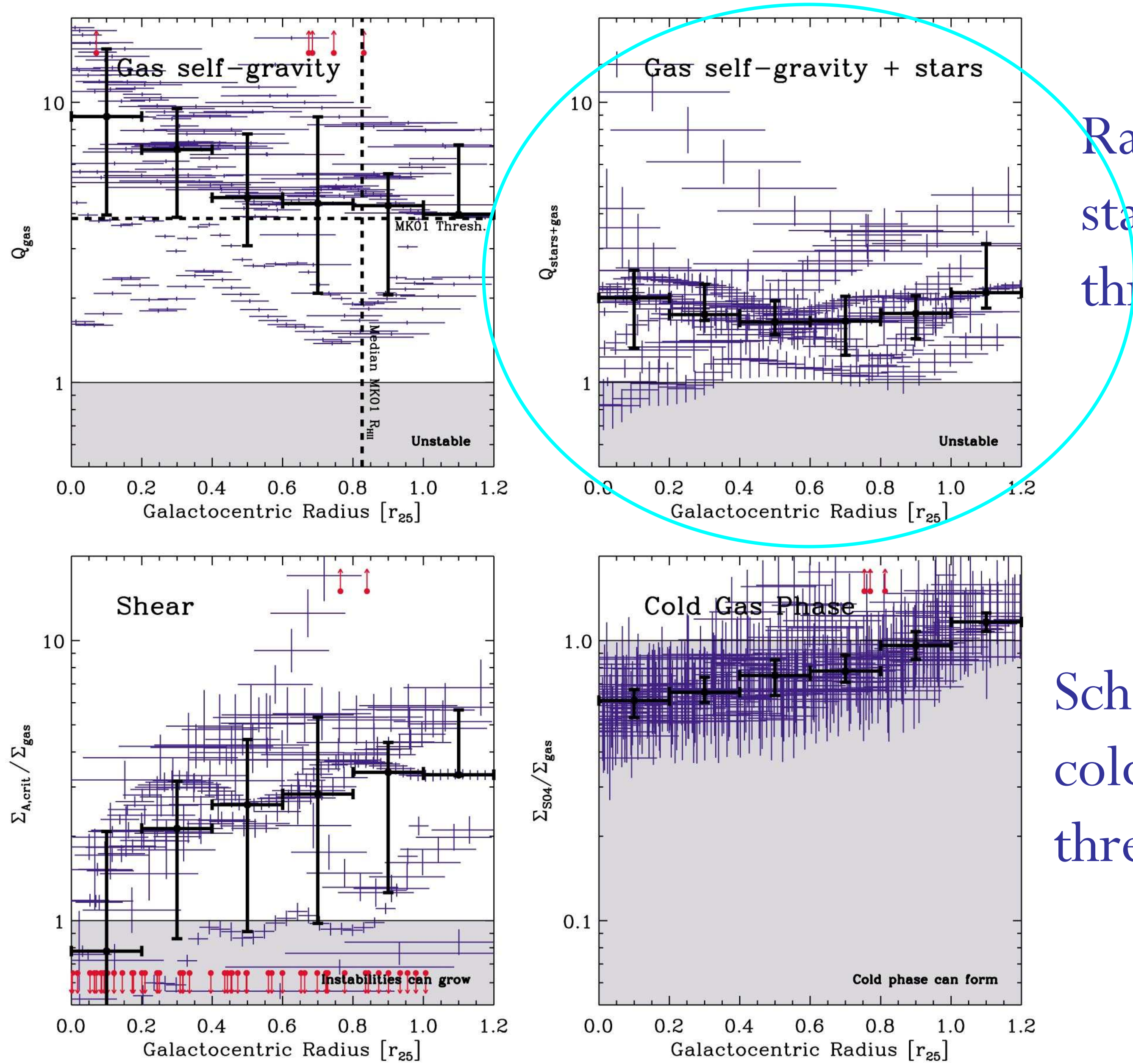
magenta is H_2-dominated, blue=HI dominated

Leroy + 08

Qgas

Dwarfs

Shear threshold (k→A)



Rafikov 01 star+gas threshold

Schaye 04 cold phase threshold

Leroy + 08

Stellar Energy Sources

- SNe: ~ $3x10^{-25}\,\varepsilon$ erg/s/cm^3
- HII regions, winds
  - total output = 10^{-25} erg/s/cm^3 (van Buren '85),
  - total to ISM = 10^{-28} erg/s/cm^3 (Mac Low & Klessen '04)
- Multiple SNe, winds, HII reg. (superbubbles) = $10^{-25}\,\varepsilon$ erg/s/cm^3

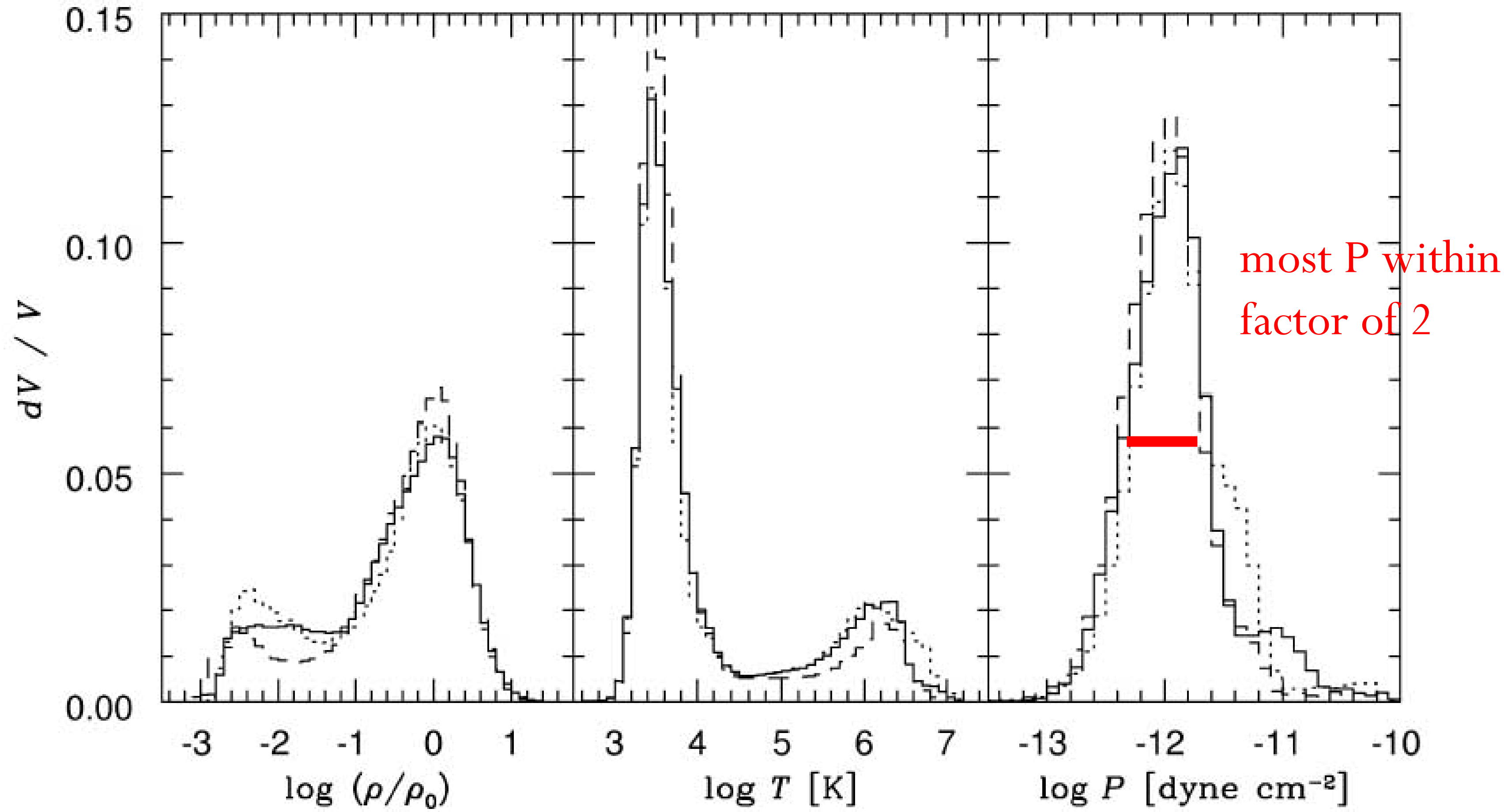
- Starlight ~ ε * Guv ~ $10^{-22}\,\varepsilon$ erg/s/cm^3

- SN/Winds/HIIR are <u>short-range forces</u>
- starlight can be long-range:
  - compressional (Spitzer 1941) or expansional (Elmegreen & Chiang 1982)

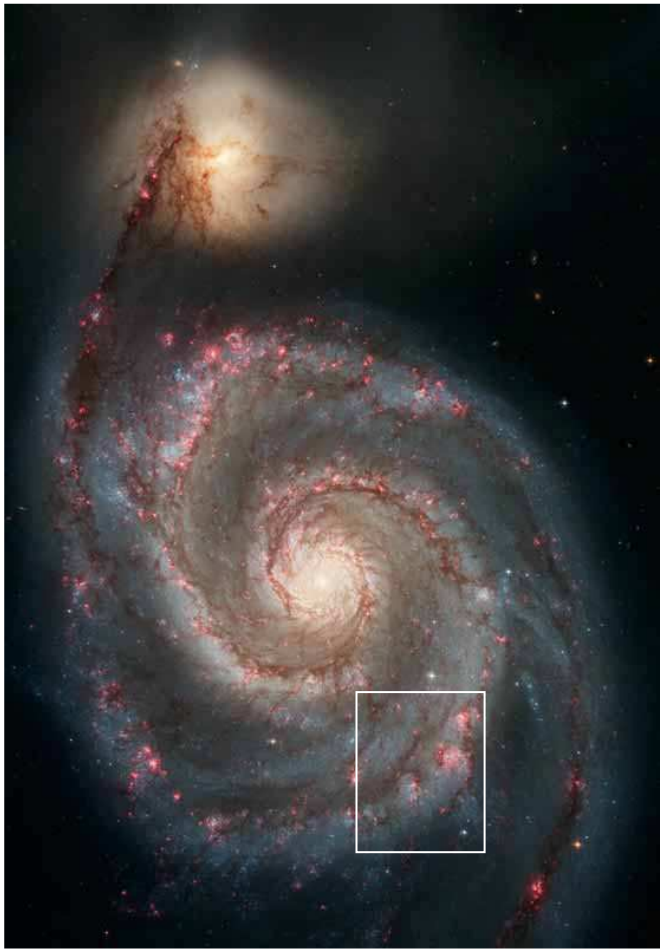
Why is Stellar Energy Input Short Range?

- SN/Winds/HIIR have expansions P(R), which gives R(t), P(t), and volume, V(P)
  - for constant rate: n(P)dP=n(t)dt with n(t) const.
    - therefore n(P)~1/(dP/dt)
  - and filling factor is f(P)=n(P)V(P)
- For HII regions: $f(P) \sim P^{-4.17}$, winds: $P^{-4.5}$, SN: $P^{-5.2}$
  - approximately, $f(P)dP \sim AP^{-4.5}dP$
- If all the volume is filled, then 1=integral f(P)dP from some P=Pmin to P=infinity
  - this give $P_{ave}=1.4P_{min}$, $f(P)=1.15(P/P_{ave})^{-4.5}/P_{ave}$
  - Thus $f(P>10P_{ave}) \sim 10^{-4}$ or $f(P>2P_{ave}) \sim 0.03$
- Most pressure bursts are within $2xP_{ave}$ for most of their lives.

- The largest pressure burst are <u>close-range and short-lived</u>

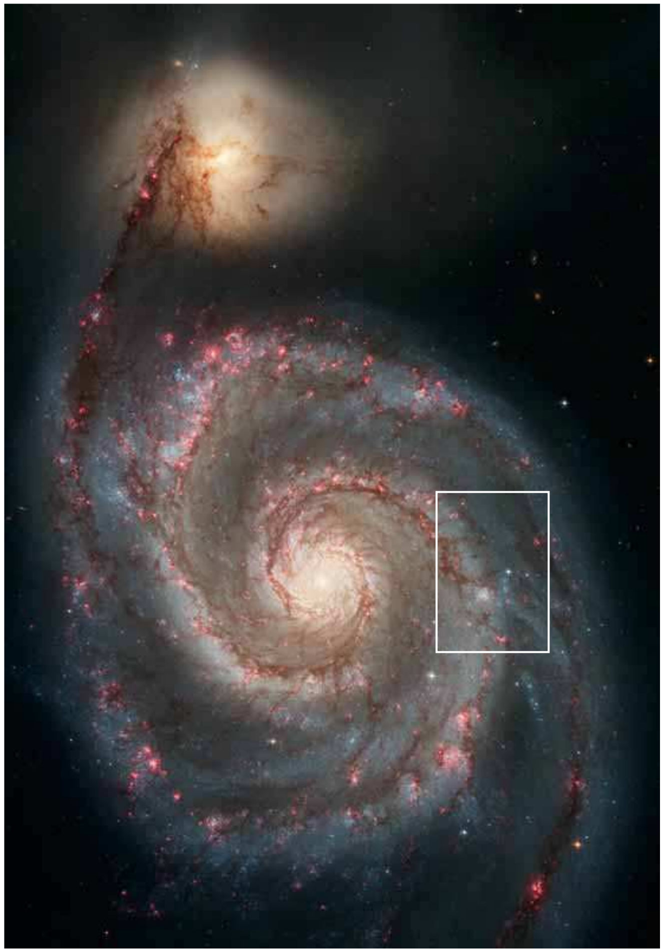


Kim, Balsara, Mac Low 2001: SPH galaxy simulation

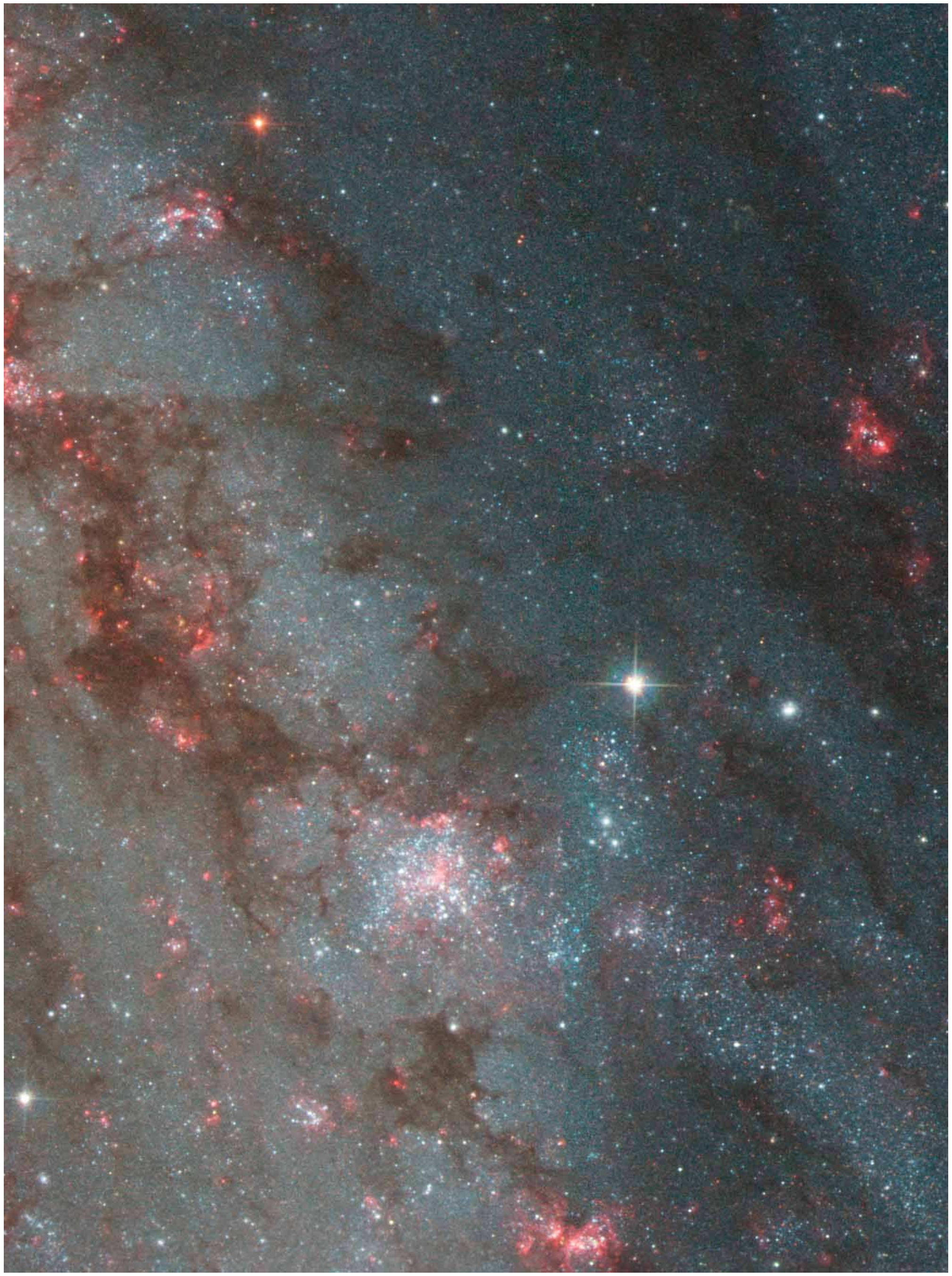


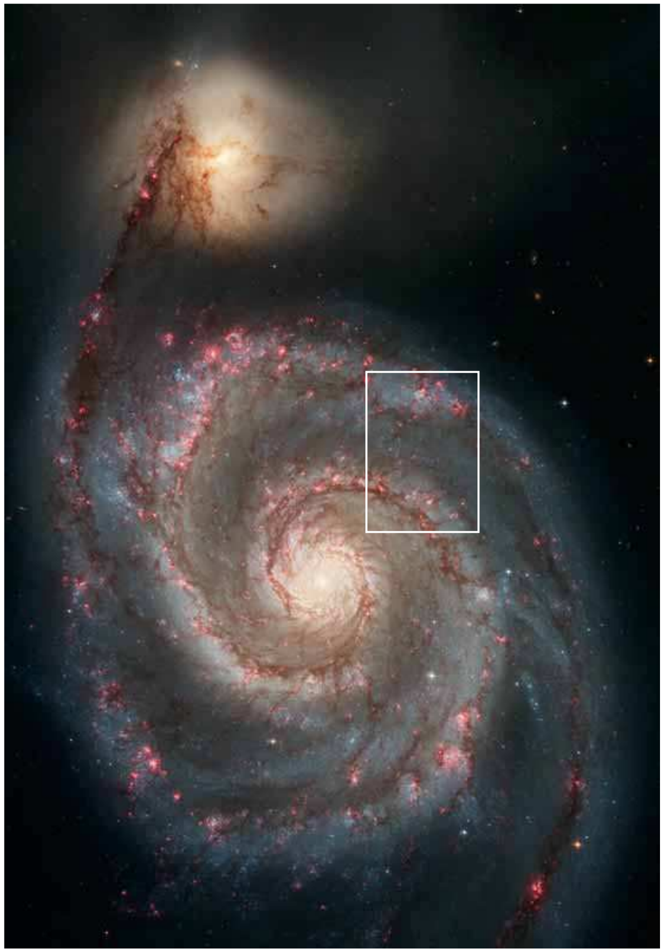
What does SF feedback look like?

Bubbles inside bubbles

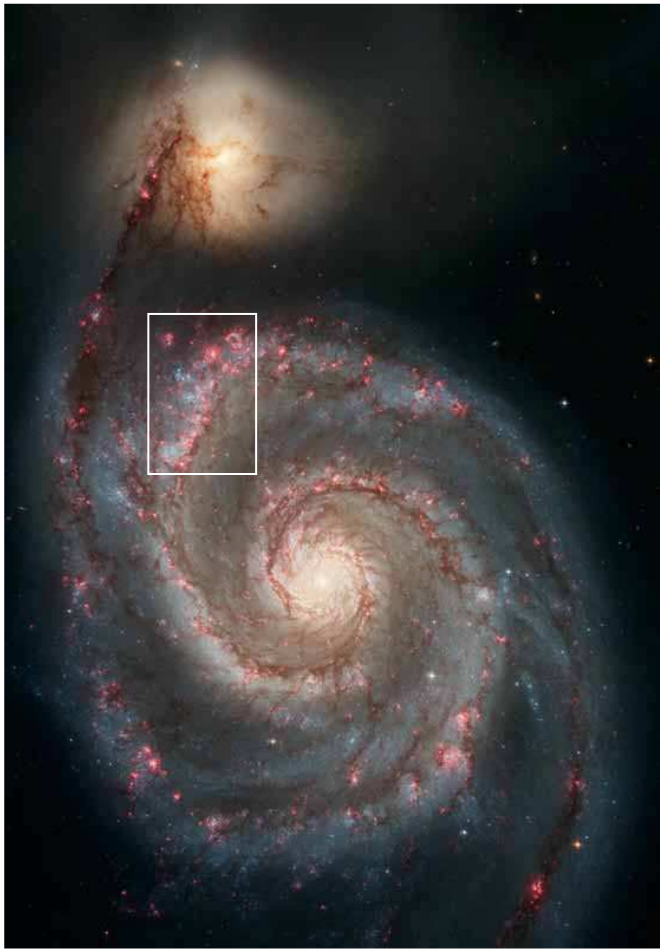


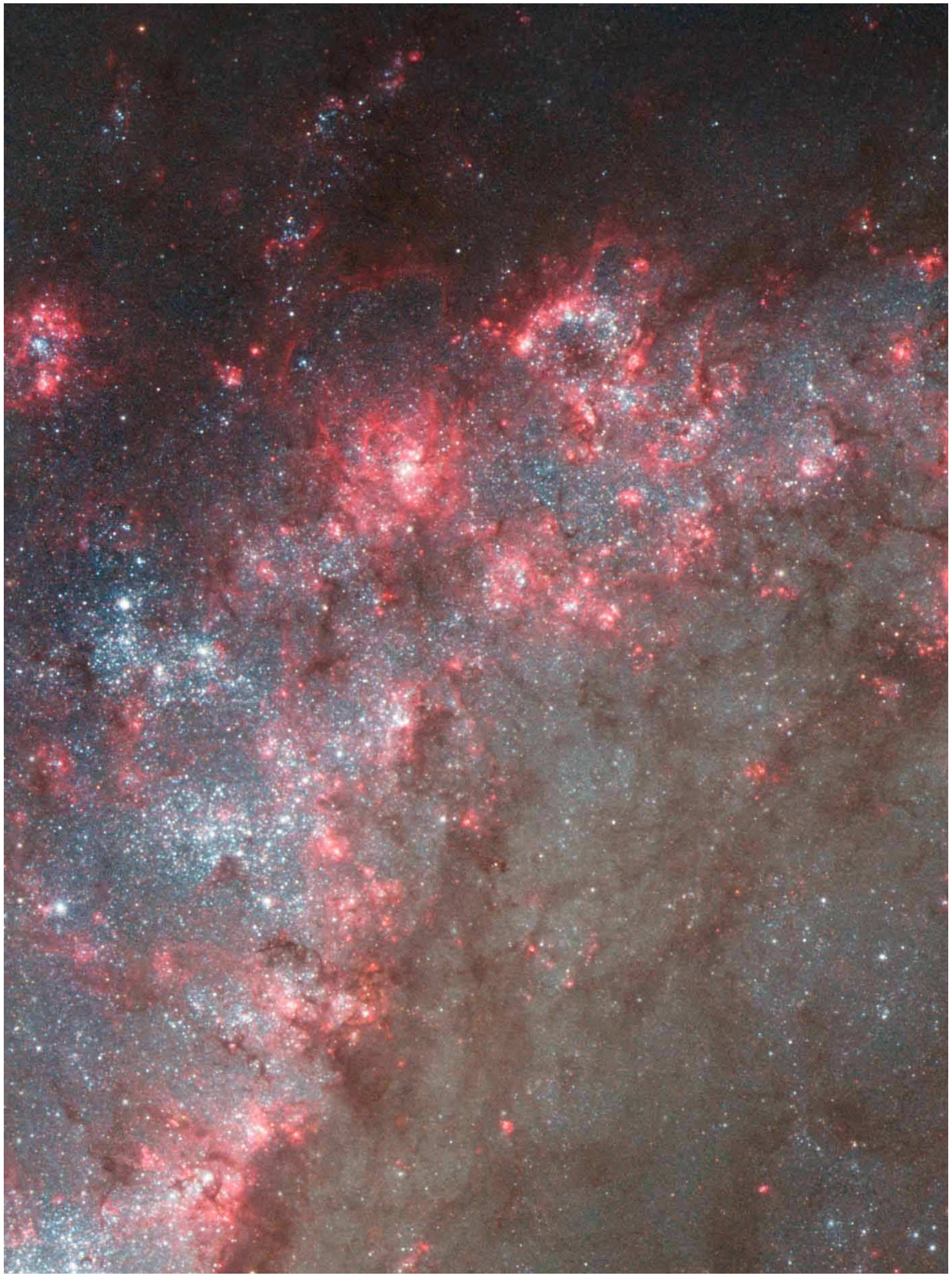
More bubbles near the arms





Old (stalled?) bubbles in the interarms





Feedback is
- localized cloud destruction
- but total kinetic energy is small compared to ~50 km/s spiral arm streaming motions for all the gas

Spiral Galaxy M74

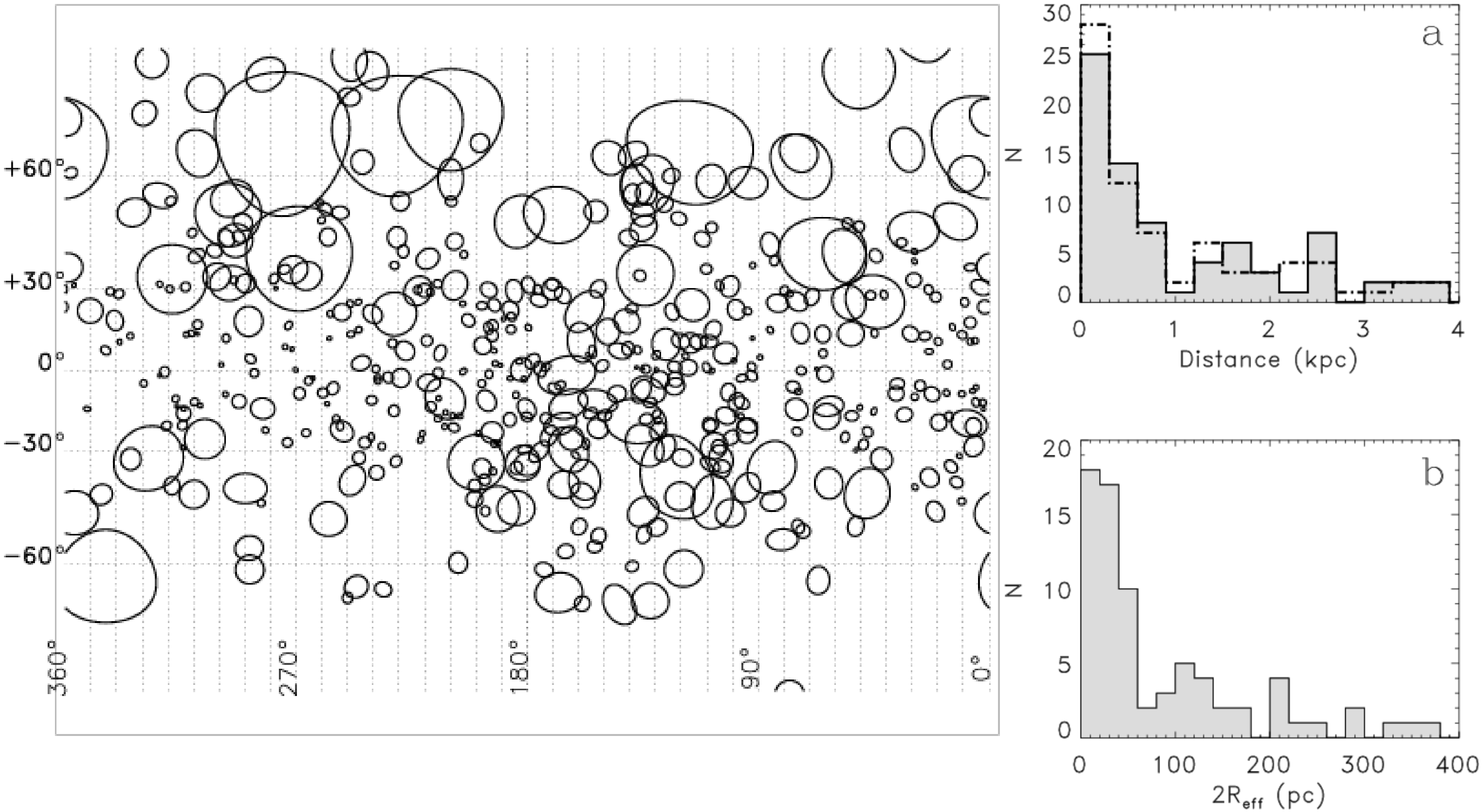
Hubble Heritage

NASA, ESA, and the Hubble Heritage Team (STScI/AURA)-ESA/Hubble Collaboration • *HST*/ACS • STScI-PRC07-41

Spiral Galaxy M101

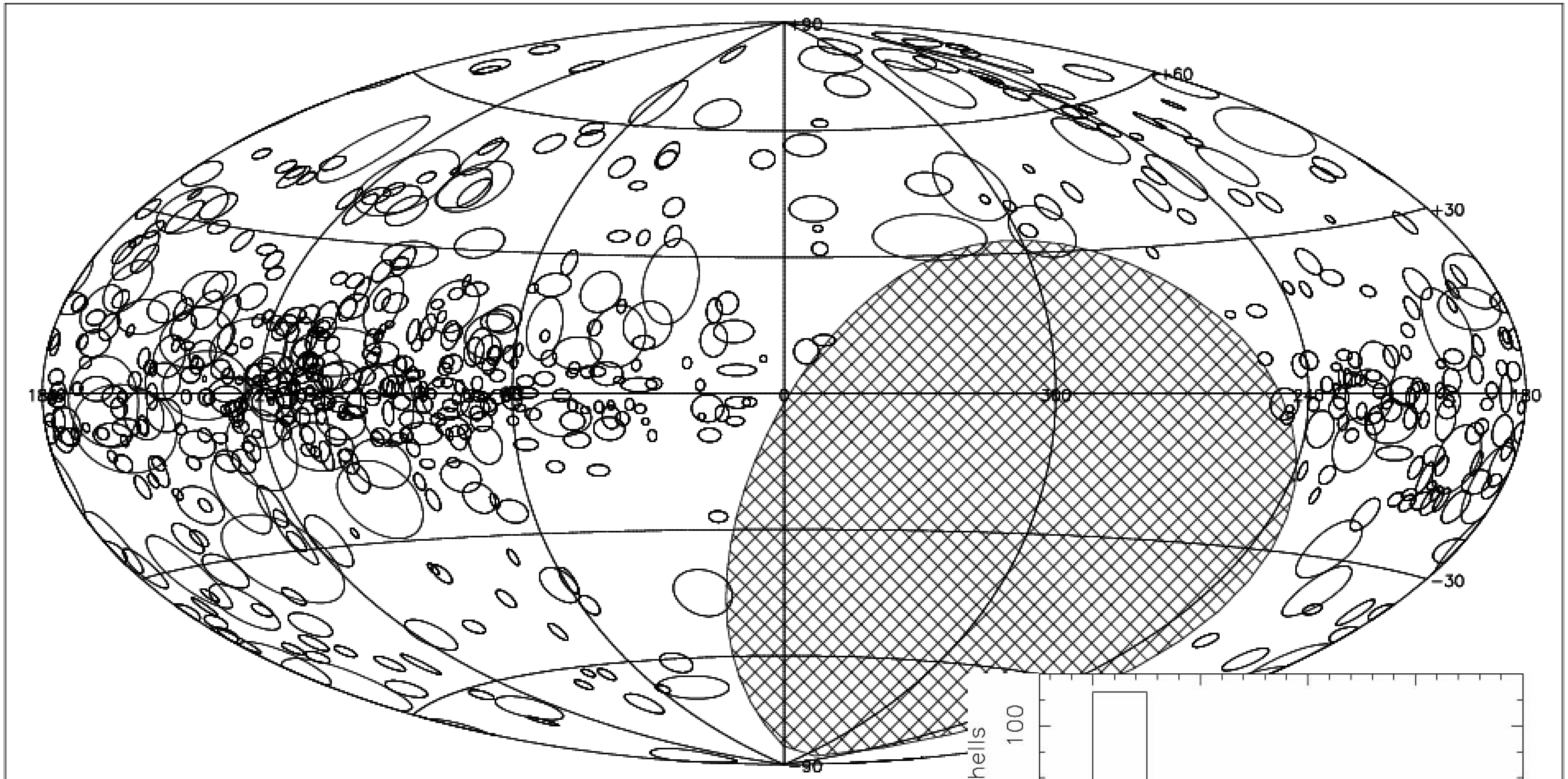
Hubble Heritage

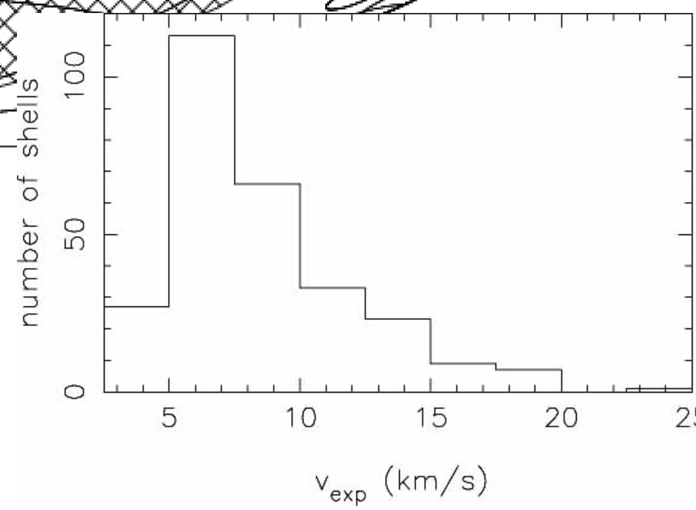
NASA, ESA, and the Hubble Heritage Team (STScI/AURA) • *HST*/ACS • STScI-PRC09-07c



Volume filling factor in inner galaxy ~ 30%
outer galaxy ~ 5%

Konyves +07 IR loops in Milky Way (from IRAS 60μ, 100μ)



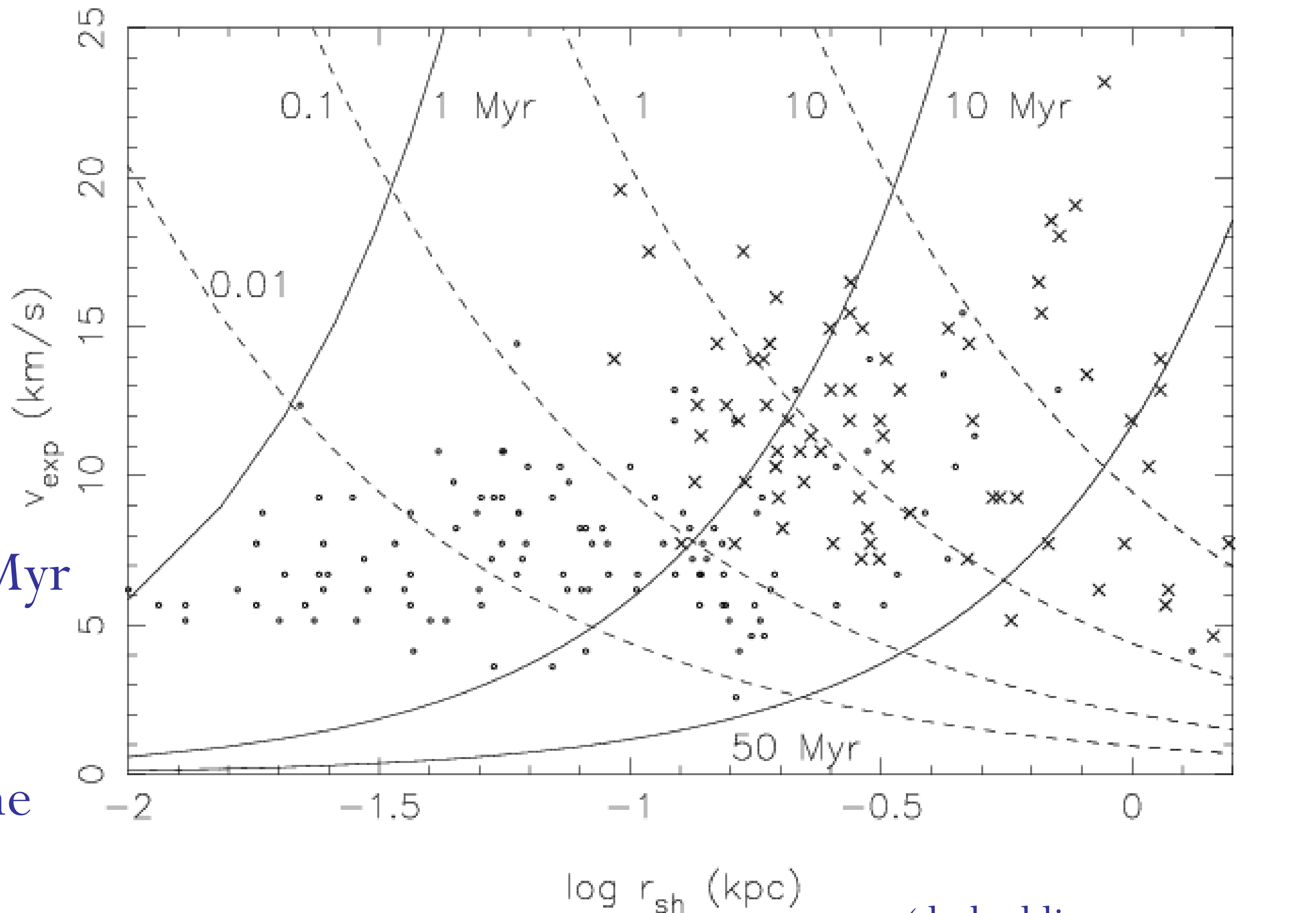


Ehlerova & Palous 05 HI shells
in the Milky Way (Leiden-Dwingeloo Survey)
5% volume filling factor

Mean age = 8.4 Myr

age/filling factor = 170 Myr

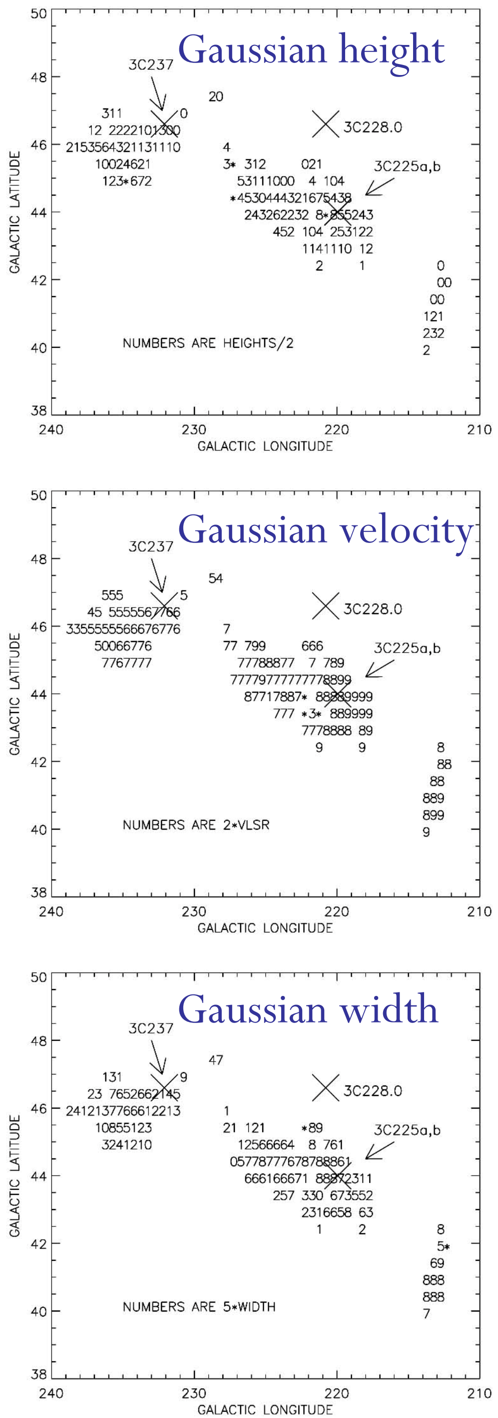
This implies all the volume of the ISM cycles through HI shells every 170 Myr (much longer than $V_{gal}/R_{SN}V_{SN}$~1Myr)



circles: E < E_{SN}
crosses E > $_{ESN}$

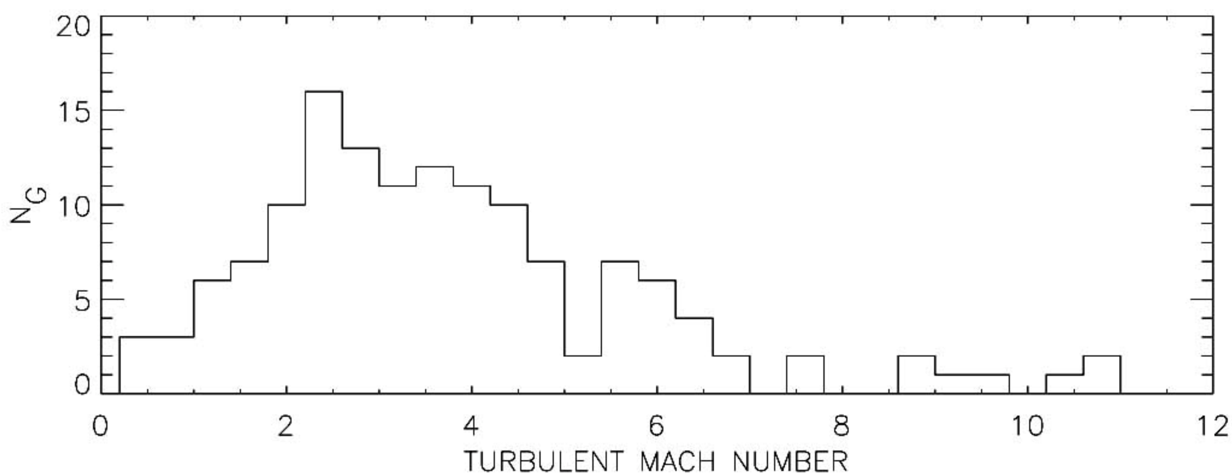
(dashed lines= constant L/n in SN-cm^3/Myr; solid lines= Age)

Ehlerova & Palous 05



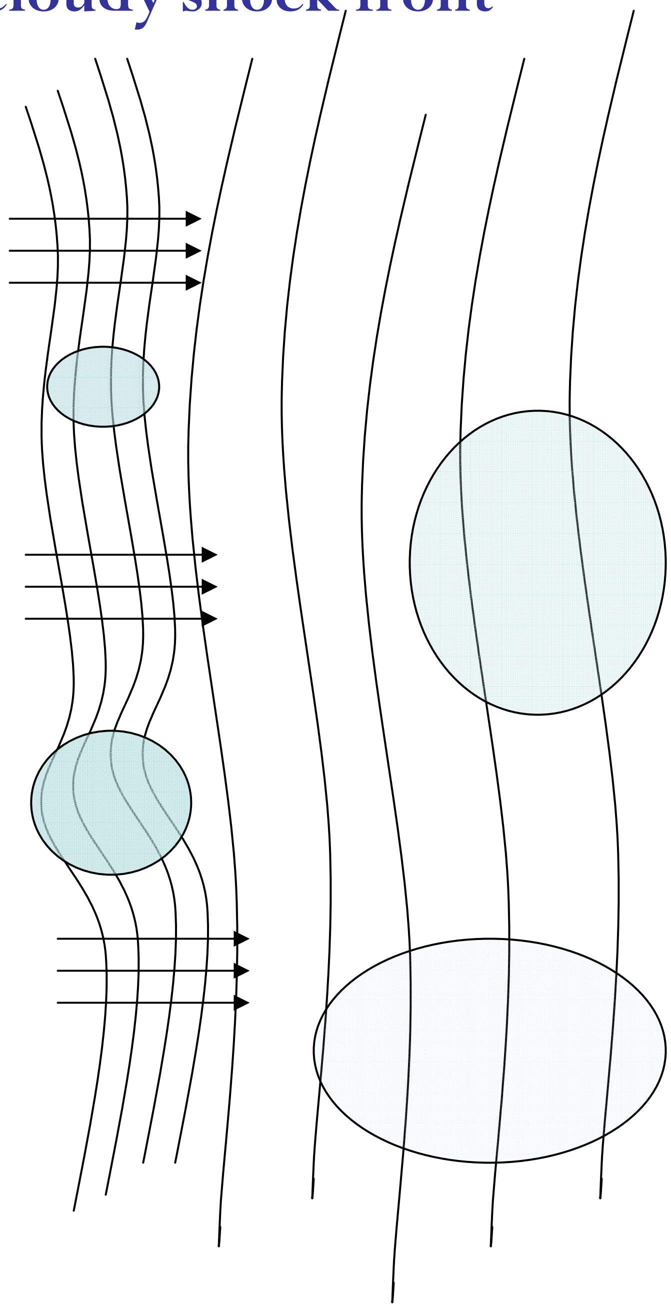
Heiles & Troland 03: traced HI absorption features over large angular distances, suggestive of ribbons extending 20° x 2°

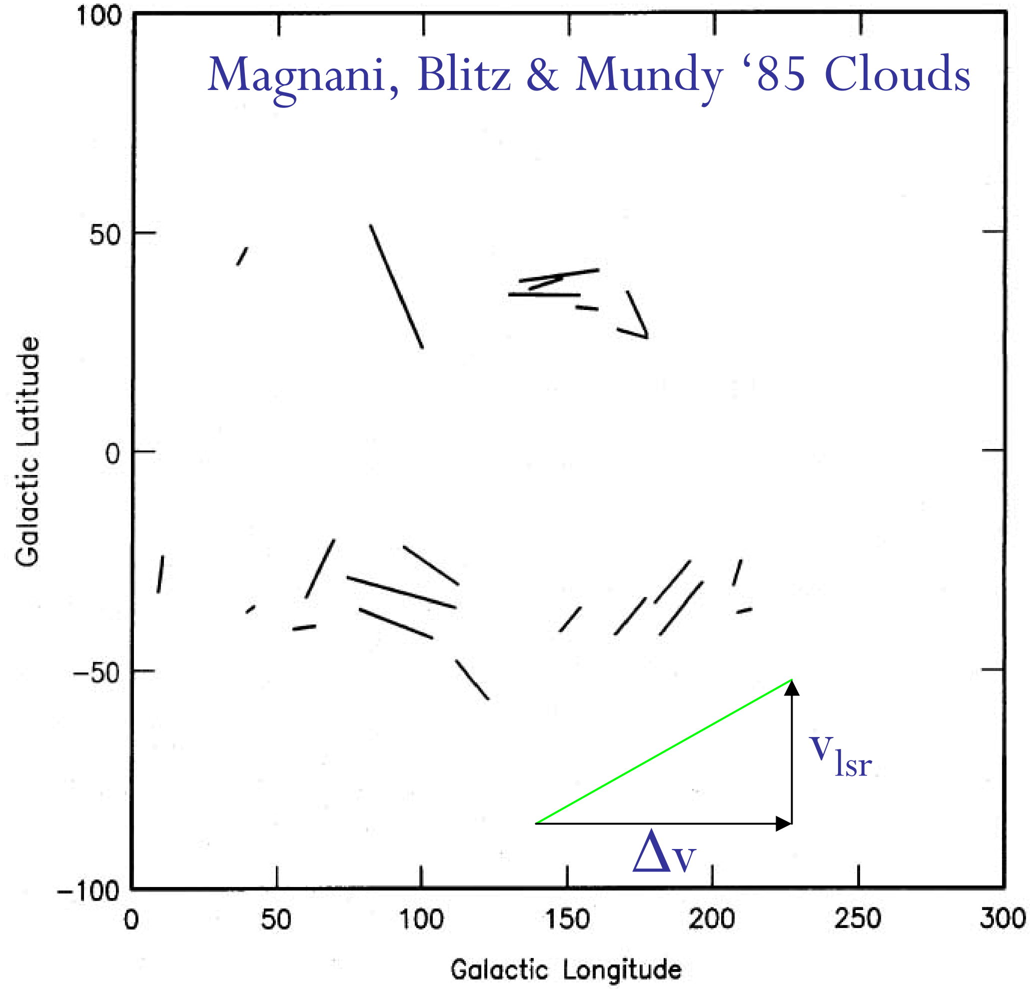
These are bands of CNM diffuse clouds. Their internal velocity dispersions are Mach 3



Some internal turbulence may comes from stray SNe, and some could come from cloud-front accretion (Elmegreen 88)

cloudy shock front





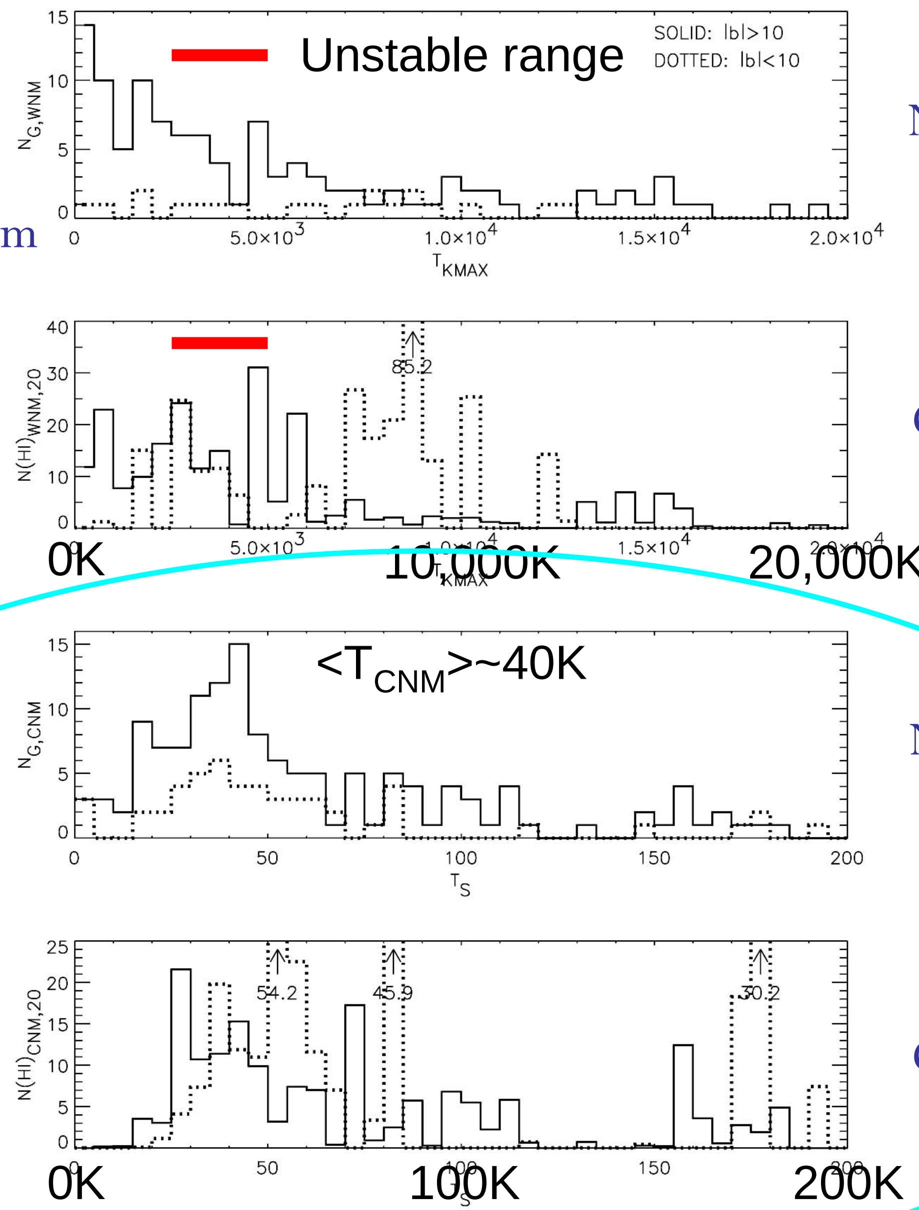
MBM cloud linewidth correlates with LSR velocity, suggesting internal turbulence from motion, as in a clumpy shock front.

Elmegreen 88

Warm Neutral Medium

Number of components

Column densities

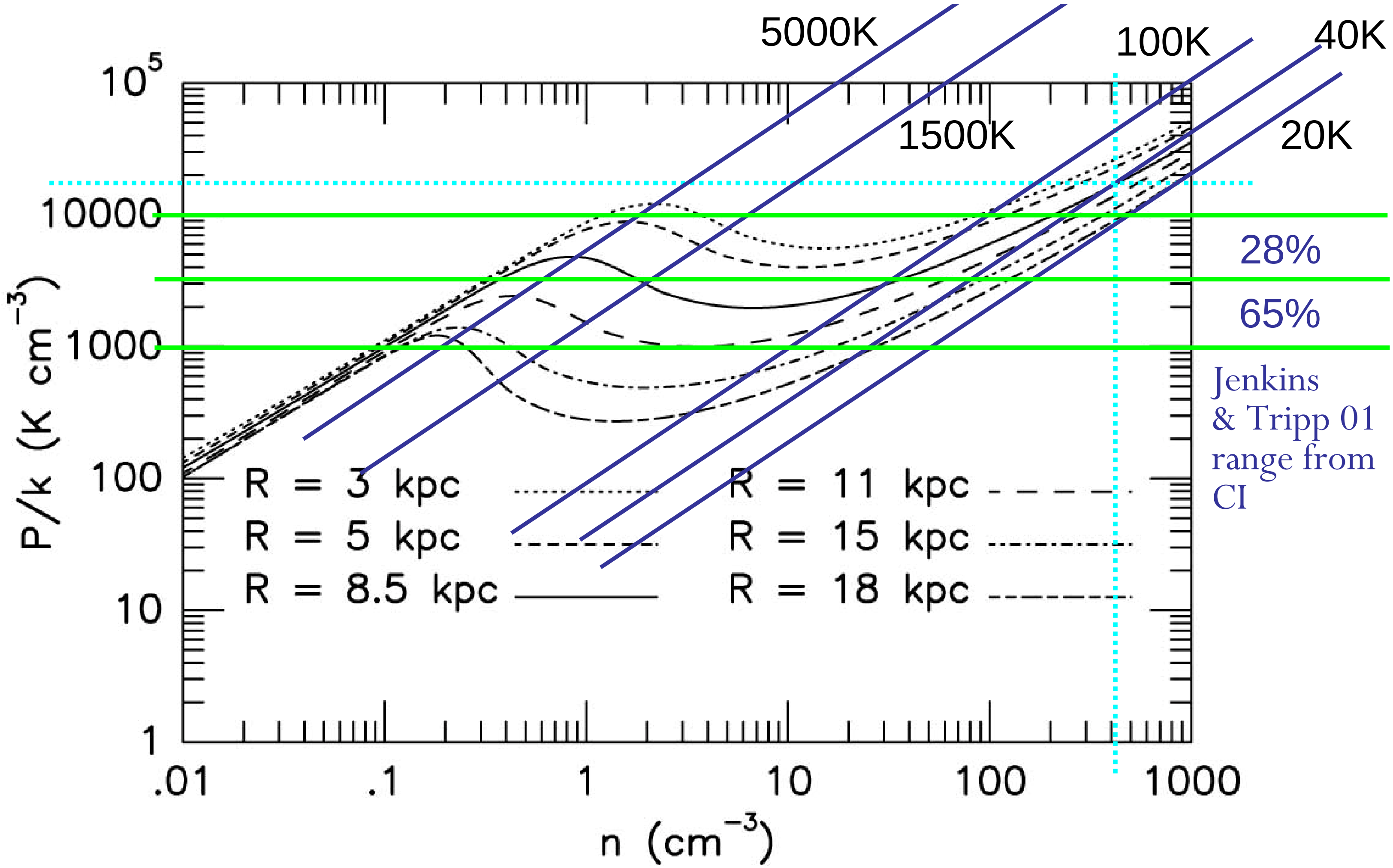


Cold Neutral Medium

Number of components

Column densities

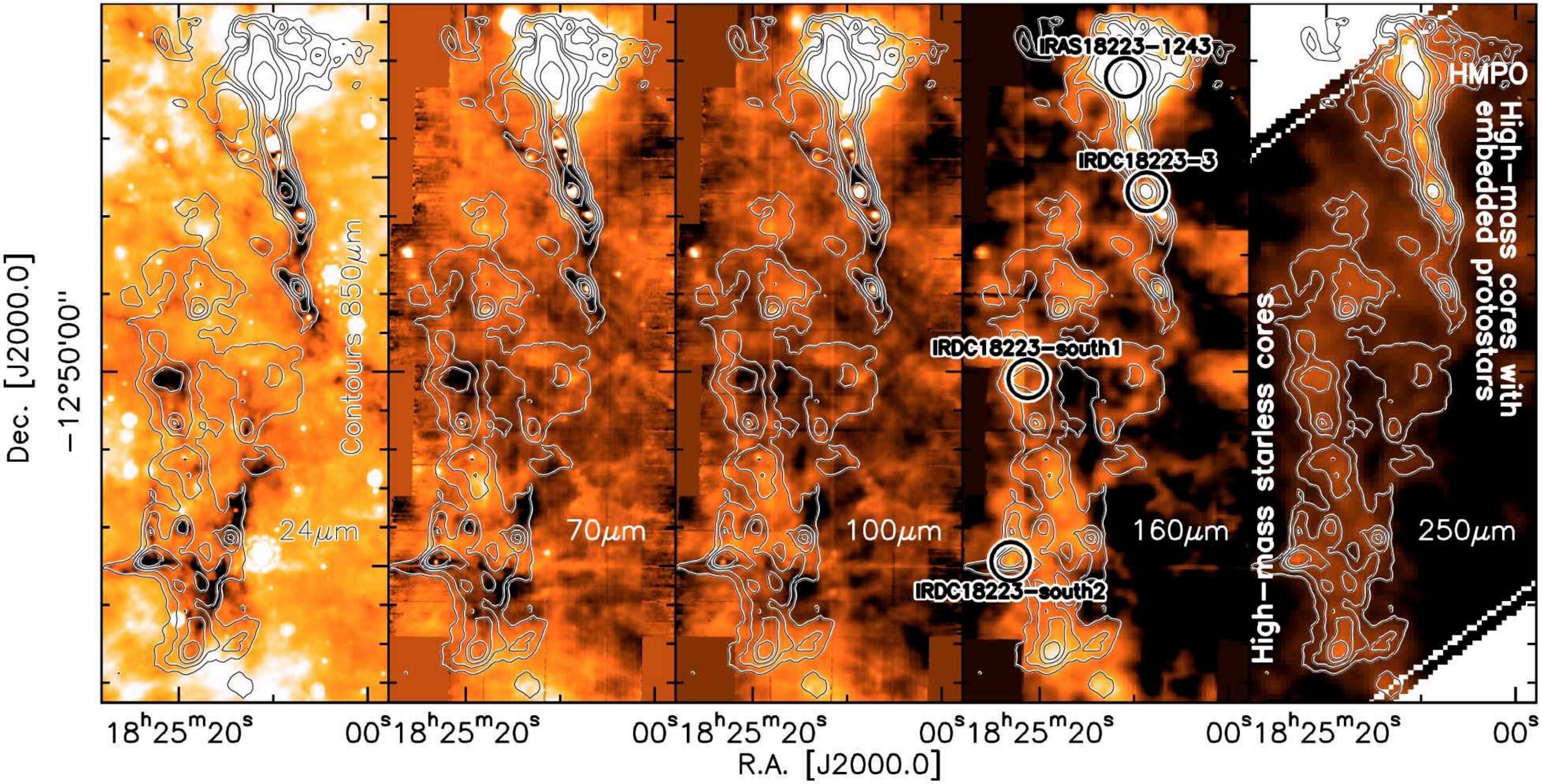
Heiles and Troland 2003: 25% of WNM (Wolfire) is in the thermally unstable range; 60% of HI is WNM with volume filling factor of ~1/2



Wolfire +03: Phase diagrams for the Milky Way, for different radii.
HI T a little too cold for 2-phase thermal equilibrium or at the observed P
Perhaps there are optical depth effects limiting heat input to diffuse clouds

Molecular Cloud dynamics may be more like gas streams on filaments than isotropic “turbulent pressure”

Guisard, ESO



Beuther +10: A region of massive star formation.

Color scale is for wavelength indicated, contours are SCUBA 850 mm.

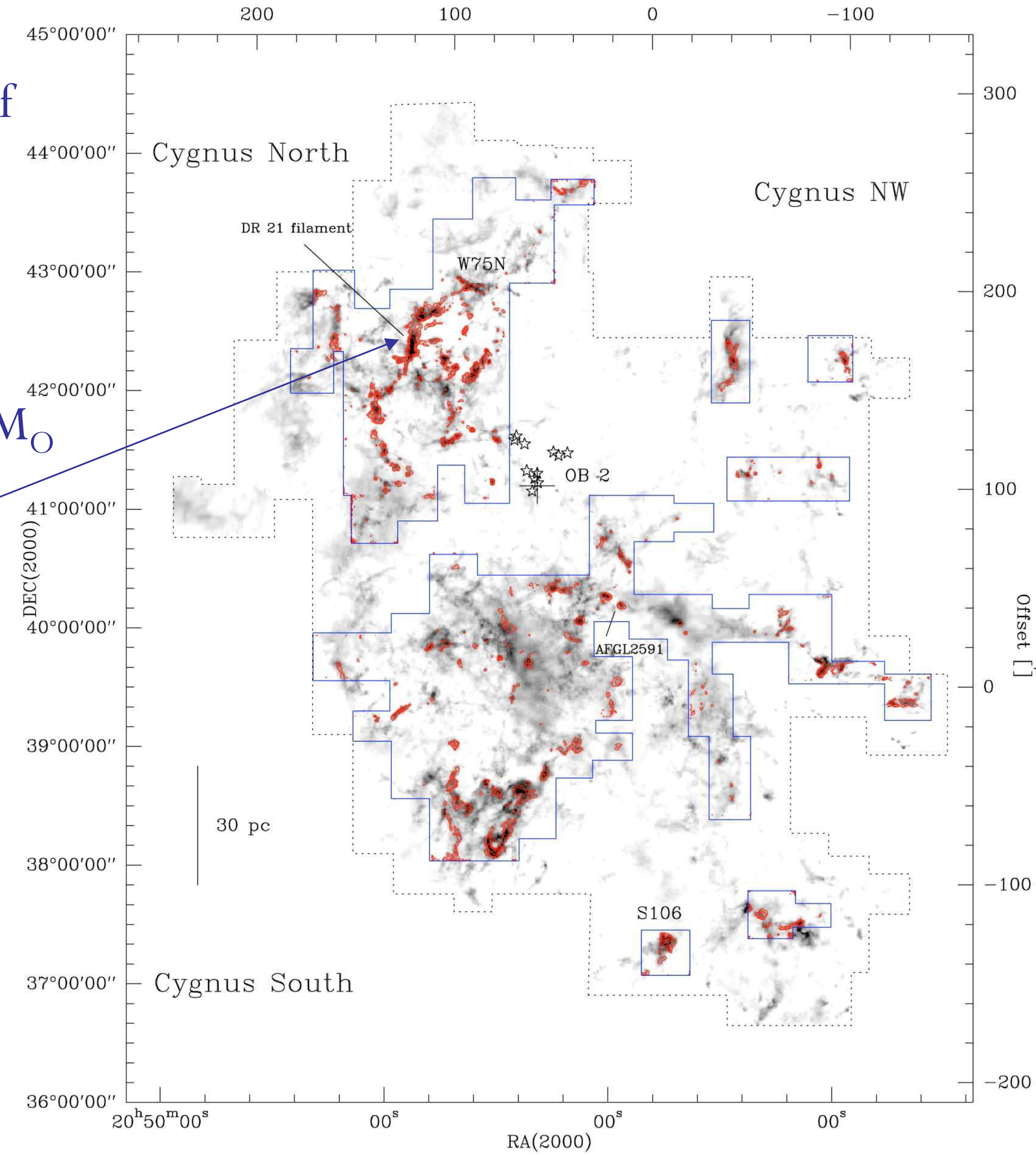
Shows a range from starless cores to starry-cores; M~170-450 M_O.

Cores are connected to filaments, from which core gas accretes

Schneider +10: A study of the DR21 filament.

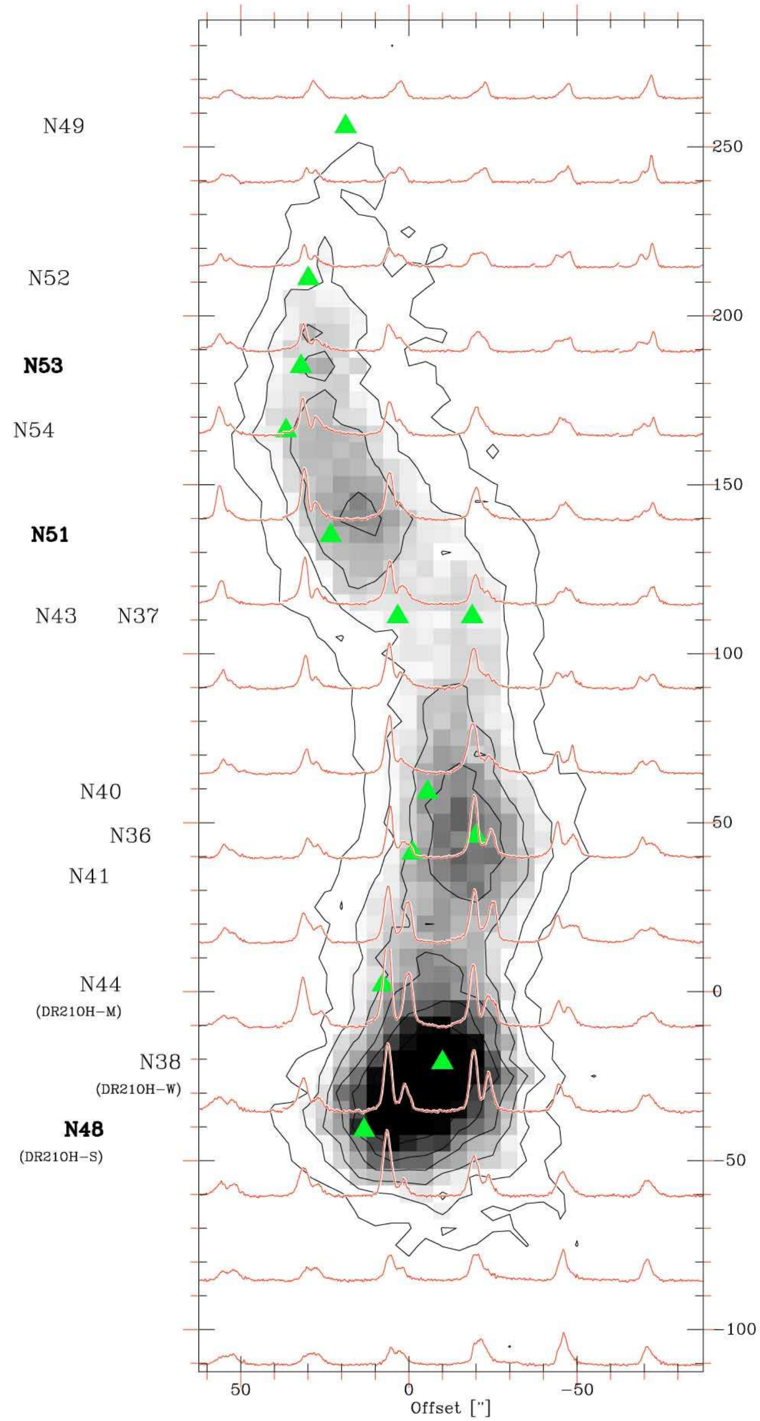
Infall motions suspected

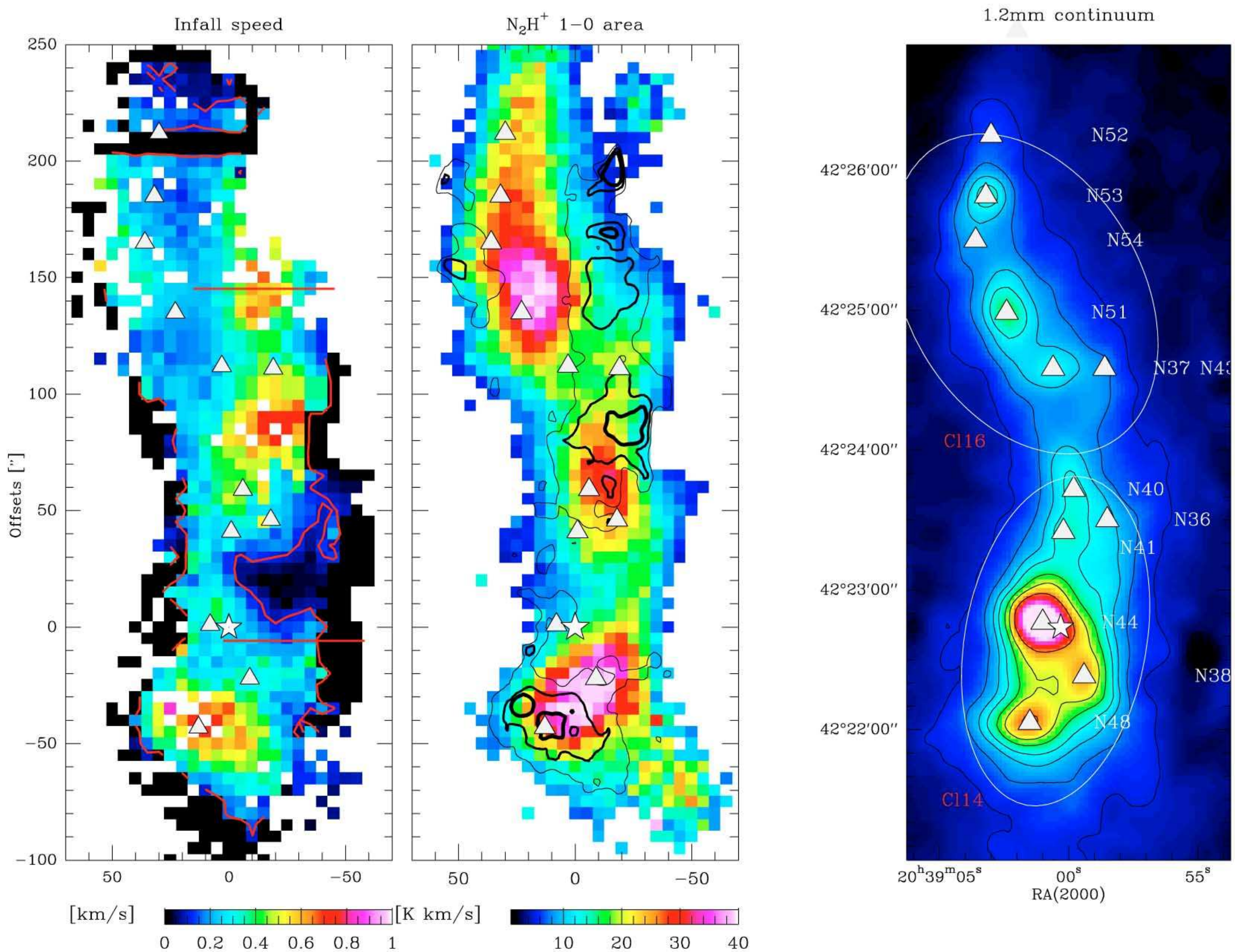
Two main clumps (3300 M_O and 4900 M_O) with accretion rates of $3 - 6 \times 10^{-3}$ M_O/yr



Emission of NH_2^+ with spectra overlaid.

Double lines suggest infall.



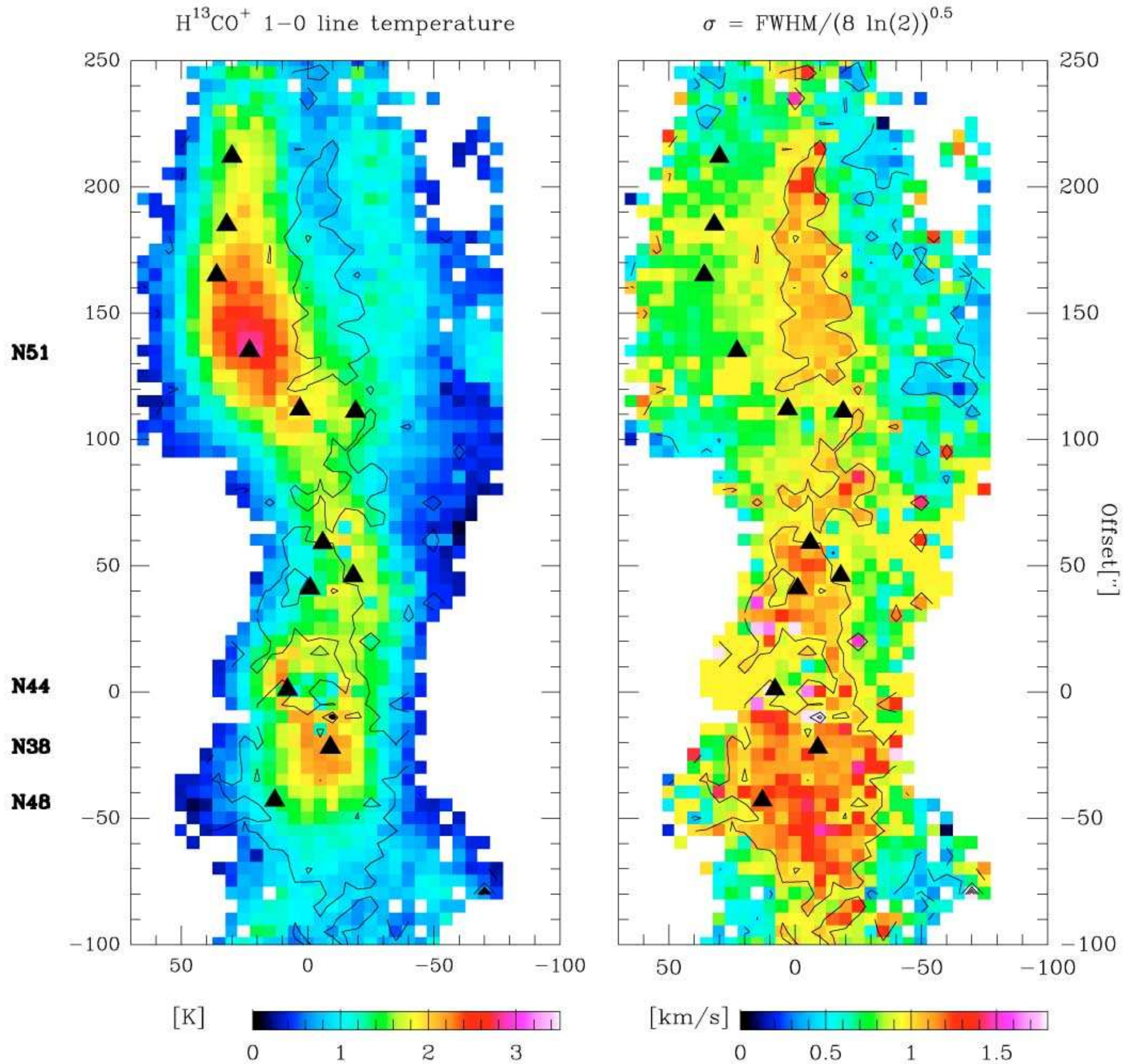


Infall speed from fits to double line profiles

Infall speed contours on N_2H^+ emission

1.2 mm continuum emission

Infall peaks are offset from the density peaks



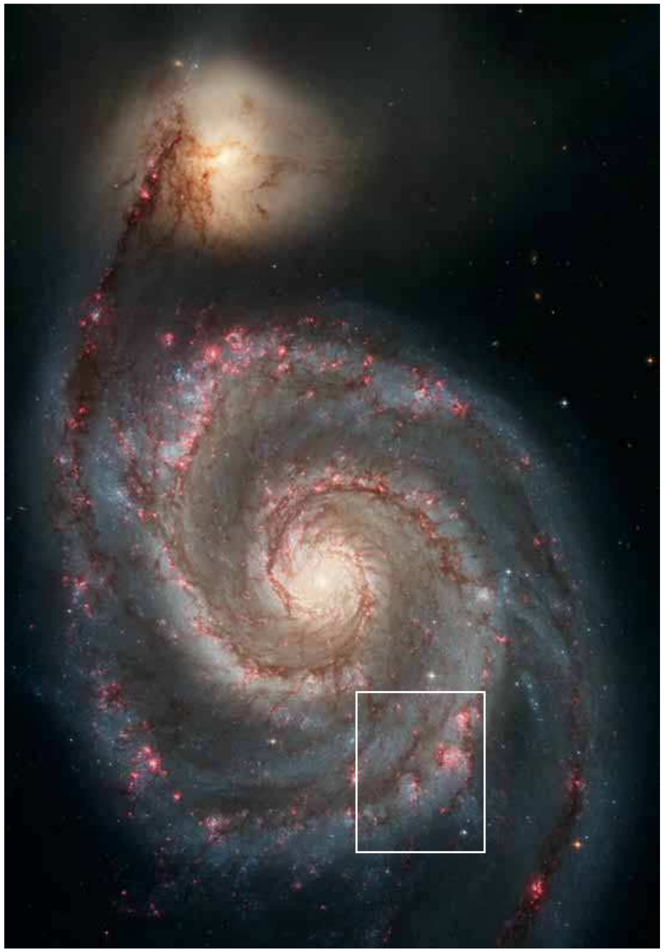
Velocity dispersion contours on $H^{13}CO^{+}$ temperature

Velocity dispersion of $H^{13}CO^{+}$

Dispersion is offset from the dense clumps: collapse and cooling at impact?

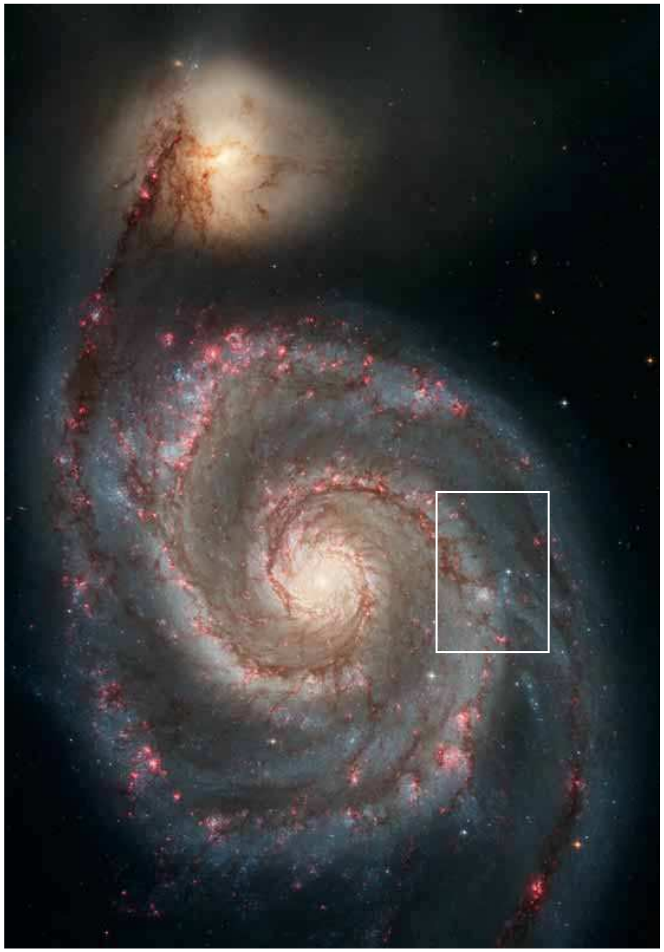
Modern View: GMCs out of Equilibrium

- Star forming parts of molecular clouds appear to be collapsing
  - SF clumps and cores are magnetically supercritical
    - not because of diffusion but because gas has drained down filaments
  - inward motions could be bulk streams, not “micro-turbulence”
    - Vazquez-Semadeni, Ballesteros-Paredes, Heitsch, Klessen, Hartmann, Elmegreen…
  - outward motions not from “isotropic turbulence” but winds
    - Nakamura & Li simulations: windy ejections, not hydrostatic equilibrium
- Cloud envelopes could be in magnetic-gravity equilibrium
  - envelopes dominate the molecular mass
  - ionization fraction is high at $A_V<4$ mag and magnetic diffusion is slow
    - Elmegreen 07, Mouschovias, Basu

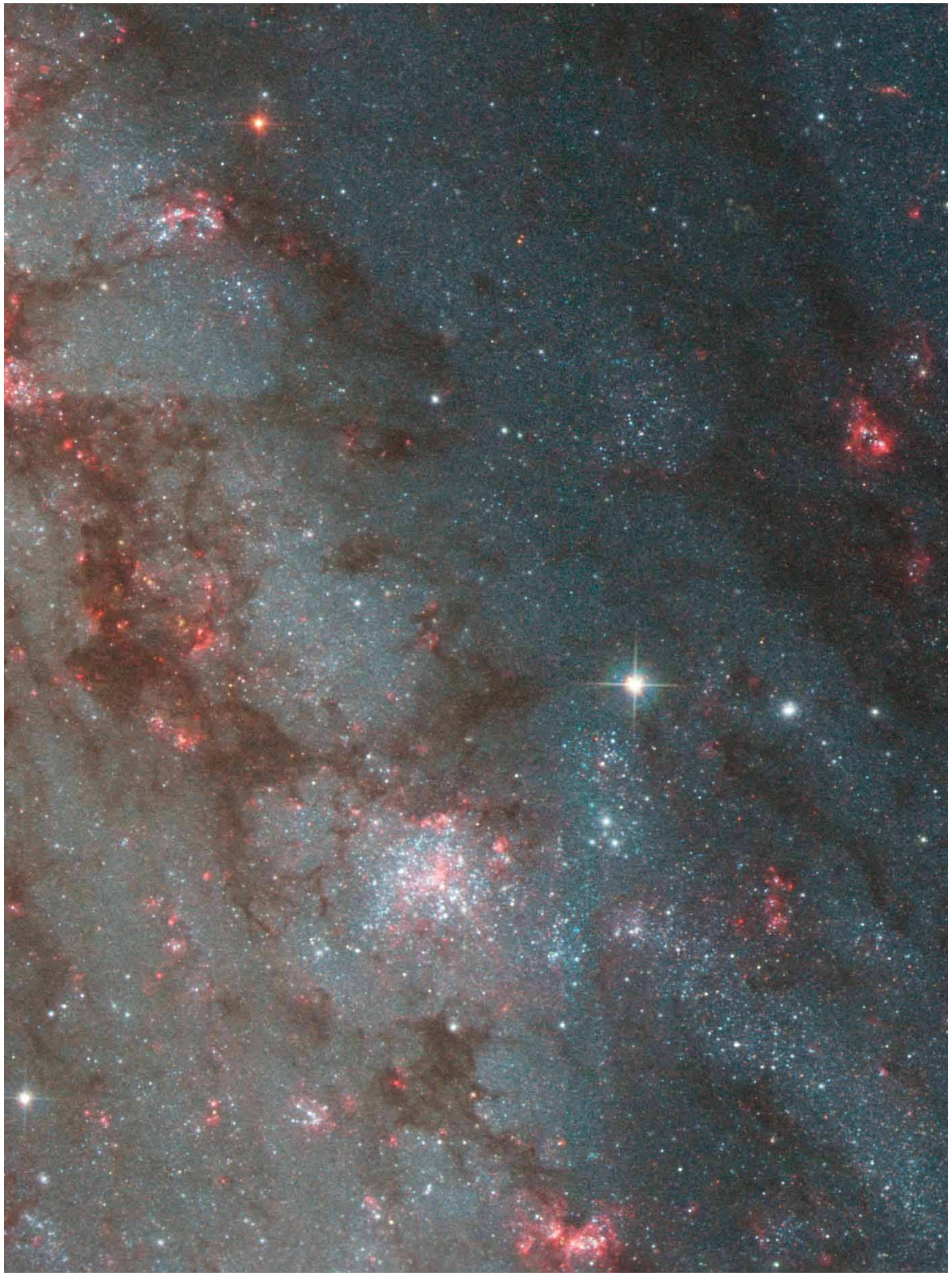


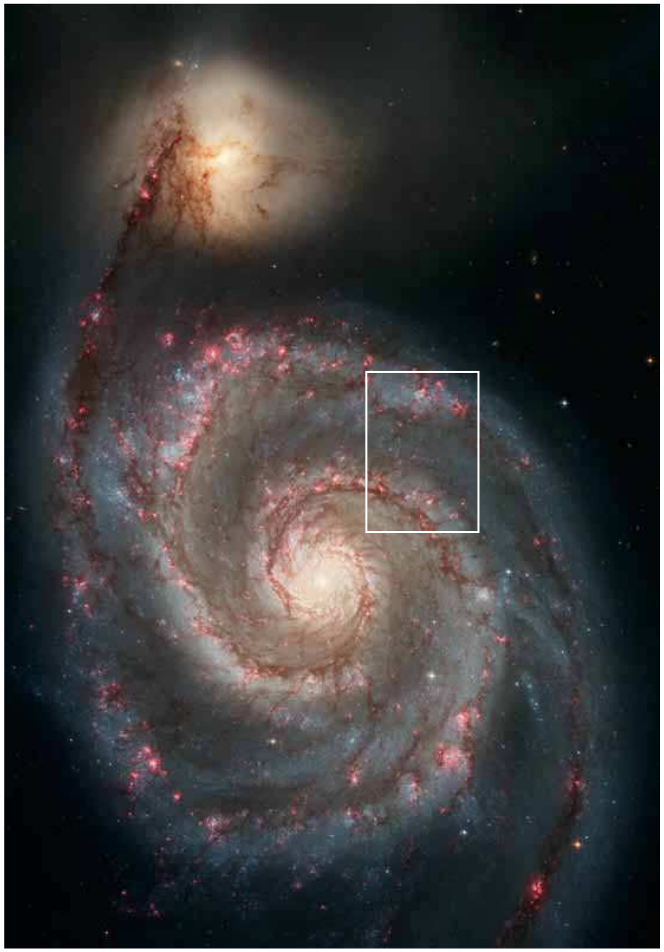
Molecular Cloud Debris

Lingering and Triggered SF



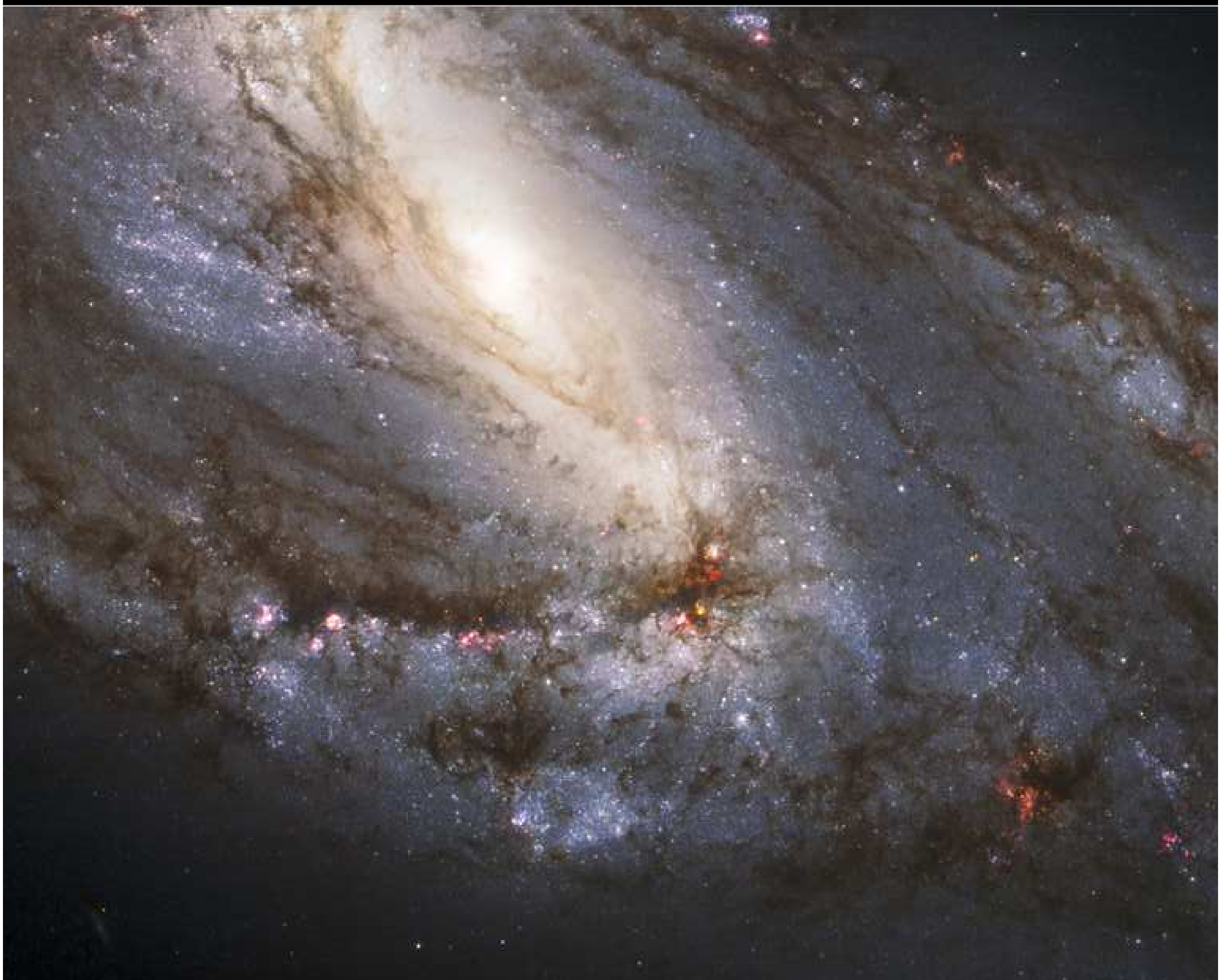
Interarms filled with mostly
inactive dark clouds





Diffuse dark clouds should be molecular

They are 50-100 Myr downstream from the spiral shock ral Galaxy M66



NASA, ESA, and the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration • HST ACS/WFC

Summary: Detailed Balance without Equilibrium

- Constant ISM instabilities pump turbulence and magnetic energy
  - MRI/Parker Inst.; SDW shock flapping, spiral instabilities from gravity
  - spiral streaming motions ARE the supersonic turbulence on large scales
  - turbulence compression and self-gravity drive cloud formation in supersonic media
  - thermal instabilities drive cloud formation in subsonic media
- The temperature changes as the density changes
  - thermal equilibrium is rapidly established although some gas lags in T
- GMC cores collapse in near free-fall, gas is used up in cluster-forming regions, winds/jets/HIIR/SN remove residual core gas
- GMC envelopes may be stabilized for 100 Myr by magnetic fields

THE END